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THE MINERALOGRAPHY OF THE FELDSPARS

PART I

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Introduction
(Crystalline) Solid Solutions
Isomorphism and Solid Solutions
The Feldspar Components
The Potassium Component
Orthoclase
Microcline
Dimorphism of the Potassium Component
The Sodium Component
Albite
Barbierite
The Calcium Component
Anorthite
The Barium Component
Celsian
Carnegieite
Two-Component Systems
The Soda-Lime Feldspars—Plagioclase Series
The properties of the Soda-lime Feldspars
Classification of the Plagioclase Series
The Potash-Soda Feldspars—The Perthite Series
Undercooling
Specific Gravities of the Potash-Soda Feldspars
The Optical Properties of the Potash-Soda Feldspars
Classification of the Potash-Soda Feldspars
The Potash-Lime Feldspars—The "Oranite" Series
The Barium-Potash Feldspars—Hyalophane Series

Three-Component Systems
Ternary Diagrams
The Potash-Soda-Lime Feldspars
Physical Properties of the Potash-Soda-Lime Feldspars
Extinction Angles
Specific Gravities
Classification
Examination of Chemical Analyses of Feldspars
Microscopic Examination of Natural Feldspars
Examples of Plagioclase Feldspars
Examples of Potash-Soda Feldspars
Applications of the Mineralography of the Feldspars to Geological Problems
Case One—Location of a Fault
Case Two—Ortho-amphibolites versus Paramphibolites
Appendix
The Solubilities of the Feldspar Components
Conclusions

INTRODUCTION

The rock-forming minerals can be studied (1) as solids capable of assuming definite geometrical forms—crystallography; (2) as optical media that affect light in characteristic ways—determinative petrography; (3) as chemical substances—the chemistry of silicon compounds; and (4) as the end products of crystallization of melts—geophysical chemistry, or as here proposed—mineralography.

This last classification embodies the point of view which has been adopted in this paper for the study of the feldspars, treating them as chemical substances formed by the solidification of melts. When the important mineral groups are fully examined, and their various thermo-equilibrium diagrams published, then the interpretative petrographer will be able to unravel the life-histories of rocks with much greater accuracy and in finer detail than is possible at present.

Appreciating the value of metallographic methods as applied to the elucidation of the feldspar system, it is therefore proposed that these silicates be examined with the aid of the phase rule. The phase rule has shed a flood of light upon the nature and constitution of alloys, and promises to be of equal value in the study of magmas and their crystallization into igneous rocks.

The components here considered are the K-, Na-, Ca-, and Ba-feldspars, which are assumed to be stable under the conditions of the present investigation. There is no difficulty in understanding the term "component" employed here as an example of the nomenclature of the phase rule. It is well for the purpose of this discussion that we understand the term "phase." "Phases are the homogeneous states, whether of freedom, solution, or combination, and whether solid, liquid, or gaseous, into which the components present pass or group themselves . . . . the phases are the transitory stages, states, or conditions, physical or chemical, through which the components pass as they are heated up and cooled down, or as their pressure rises and falls."[1]

The mathematics of the phase rule applies to systems which are in a state of perfect equilibrium. It cannot be disputed that many metallic alloys and silicate complexes (silicate alloys) are in a state of imperfect or false equilibrium. So frequently does this condition occur that the phase-rule method of considering such systems has been the object of considerable criticism. These critics are entirely justified so far as the strict application of the rule is concerned, but apparently overlook the value of thermo-equilibrium diagrams. The use of the diagrams and the application of the phase rule are distinct. Such diagrams help to explain the phenomena of crystallization and microscopic textures of silicate and metallic alloys. Howe[2] points out that hardened steel is a metastable system, that is, it is not in equilibrium, and yet that fact does not depreciate the value of the iron-carbon diagram to the steel manufacturer. A condition of imperfect equilibrium can be definitely indicated upon the diagram. Ostwald[3] says: "In spite of my great admiration for the progress that has been made in metallography through the introduction into this field of the concepts of chemical equilibrium, the phase rule and van't Hoff's concept of solid solution, I cannot help emphasizing the need of caution in all this, for those concepts are all based upon the truth

[1] H. M. Howe, *The Metallography of Steel and Cast Iron*, 1916, p. 240.

[2] *Ibid.*, p. 231.

[3] Wolfgang Oswald, *Theoretical and Applied Colloid Chemistry*, translated by Martin H. Fischer (1917), p. 198.

of certain assumptions. . . . . The belief that true equilibria are attained in these solid mixtures . . . . lacks support."

This quotation is quite typical of such criticisms: it gives the impression that in studying a system, such as the feldspars, by means of the phase rule the laws of physical chemistry are violated. Metallographers such as Howe, for example, are recognizing the metastability of many systems. Many feldspars are metastable solid solutions.

It would appear that the most satisfactory method of attack would be a laboratory study of the melting and freezing phenomena of the feldspars. The work of Allen and Day[1] has shown, however, that little information can be secured through this means because of the high viscosity of the alkali feldspars when above their fusion temperatures. Even when in a molten condition it is impossible to effect crystallization. Watts[2] using pyrometric cones in his work upon artificial mixtures of natural potash-soda feldspars has found it very difficult if not impossible to secure reliable thermal data.

Thus the method of attack here is in part a reverse process. By a study of textures and properties of various specimens differing in their chemical composition, the thermo-equilibrium diagrams of the binary systems can be inferred by analogy with the diagrams of other systems and by means of suggestions found in the metallurgical and mineralogical literature. The writer suggests that the application of the methods of the metallographer to the study of silicate systems for the purpose of increasing our knowledge concerning them may properly be called the science of mineralography.

Murdoch[3] has already proposed the use of this term in a slightly different sense to cover the employment of the metallurgical (metallographic) microscope in the study of non-transparent minerals in the same way that it has been used for years in the study of metals.

[1] E. T. Allen and A. L. Day, "The Isomorphism and Thermal Properties of the [Plagioclase] Feldspars," *Carnegie Inst. of Wash. Pub. 31*, 1905.

[2] A. S. Watts, "The Feldspars of the New England and North Appalachian States," *U.S. Bur. Mines Bull. 92*, 1916.

[3] Joseph Murdoch, *Microscopial Determination of the Opaque Minerals*, 1916, p. iii.

It seems to the writer that the analogy is not perfect. Metallography deals with the constitution, crystallization, and microscopic textures of metallic alloys and their relation to their physical properties. Such study must necessarily be guided by constant references to the thermo-equilibrium diagram of the system under consideration. In the examination of opaque minerals, such as the sulphide ores, the diagrams are not at hand, and not until then should the term mineralography be employed. Furthermore it is questionable whether it is best to limit mineralography to the opaques as contrasted with the transparent minerals. Mineralogy and petrography become mineralographic when the phase rule is considered and the interpretation of mineral compositions and rock textures studied in the light it sheds upon them. This paper is an attempt to discuss the essential nature and relationships of the feldspars, together with an explanation of the methods used in studying them. Discussions of some phases of this subject have appeared in German, but no adequate study of the entire system has been attempted in this country. The following brief summary indicates the substance of the discussion, though not the precise order of presentation.

Many of the principles that apply to metallography and metals apply also to minerals. One of these essential principles is that of solid solutions. To handle this principle the method known to physical chemists as the phase rule has been applied to metallography, necessitating the construction and interpretation of thermo-equilibrium diagrams to set forth the constituents and the processes which form metallic alloys.

Now the principle of solid solutions is applicable also to minerals, and is indispensable to a thorough knowledge of their composition. The mineralogist and the geologist should therefore avail themselves of the phase-rule method, and should understand the use of its diagrams if they would thoroughly grasp the nature of the constituents and of the physical phenomena which have given them their rocks and minerals, the end products of such processes.

This study involves: (1) the construction of thermo-equilibrium diagrams; (2) the interpretation of such diagrams; (3) the application of these diagrams to the rock-forming minerals.

The present-day conception of the chemical nature of the silicates is the result of slow development. In 1846 Laurent[1] suggested that the silicates should be considered to be salts of several acids rather than a single one, and by 1865 ortho-, meta-, and trisilicic acid had become a firmly established nomenclature. Later Vernadsky[2] pointed out that in some aluminum-bearing silicates the element aluminum seemed to possess the characteristics of an acid. Thus the theory that some silicates are aluminosilicates instead of simple silicates was developed and is entertained by many geochemists. While it would be instructive to follow this phase of the subject in greater detail it is outside of the main purpose of this paper. However certain aspects of the aluminosilicate theory need to be considered in attacking the problem of the relationships between the soda, potash, and lime feldspars. "Schwantke[3] while reasoning over the rôle of the lime-silicate which occurs mixed with the potash silicate $K_2Al_2Si_6O_{16}$ in orthoclase built up theoretical conclusions of much interest. . . . . In order to make the formulas of albite, anorthite, and orthoclase more analogous to each other, we may write them $Na_2Al_2Si_2Si_4O_{16}$, $K_2Al_2Si_2Si_4O_{16}$, $Ca_2Al_2Al_2Si_4O_{16}$, and $Ba_2Al_2Al_2Si_4O_{16}$."[4]

Bayley[5] says that chemically, the feldspars may be regarded as isomorphous mixtures of the four compounds, $KSiAlSi_2O_8$, $NaSiAlSi_2O_8$, $CaAlAlSi_2O_8$, and $BaAlAlSi_2O_8$, each of which except the fourth has been found nearly pure in nature. . . . . The feldspars have also been regarded as salts of the acid $H_5AlSi_2O_8$ in which the hydrogen is replaced by various radicals, thus $(KSi)AlSi_2O_8$, orthoclase; $(NaSi)AlSi_2O_8$, albite: $(CaAl)AlSi_2O_8$, anorthite; and $(BaAl)AlSi_2O_8$, celsian. There are several objections to Bayley's conceptions. In the first place, as will be pointed out later, the

[1] Laurent, "Sur les Silicates," *Comp. Rend.*, XXIII (1846), 1050–58.

[2] W. Vernadsky, "Über die Sillimanitgruppe und die Rolle des Aluminums in den Silicaten," *Bull. d. Russ. Ges. d. Naturf.*, 1891, nr. 1–100. (In Russian.)

[3] A. Schwantke, "Die Beimischung von Ca in Kalifeldspath und die Myrmekitbildung," *Centralbl. für min. Geol. und Pal.* (1909), pp. 311–18.

[4] J. J. Serderholm, "On Synantectic Minerals," *Bull. de la commo. geol. de Finlande No. 48*, 1916, pp. 90–91.

[5] William S. Bayley, *Descriptive Mineralogy*, Appleton (1917), p. 408.

feldspars do not form a complete isomorphous series. Secondly, it is not customary to regard silicon as a base-forming element.

(CRYSTALLINE) SOLID SOLUTIONS

The whole subject of solid solutions was opened up in a paper by van't Hoff[1] which appeared in 1890, bearing the title of "Solid Solutions." He said: "If we regard a solid solution as a solid, homogeneous mixture of several substances, the composition of which can be changed without destroying the homogeneity, analogous to solutions in liquids as the solvent, it should not be difficult to cite cases which belong unconditionally in this category." This definition of solid solutions gives us a concept that is a most valuable aid to the study of substances in the solid state.

Again van't Hoff defines a solution as "a homogeneous mixture, the composition of which can undergo continuous variation within the limits of its stable existence,"[2] or in other words a solid solution is a solid homogeneous complex of several substances, whose proportions may vary without loss of homogeneity. A solution may be defined in terms of the phase rule as "a homogeneous mixture which undergoes a change in composition in producing a new phase."[3] Washburn says that "a solution may be defined as a one-phase system composed of two or more molecular species."[4]

Ordinarily the term "solution" has been limited to solids dissolved in liquids. But recent investigation has shown that the conception of solutions should be extended to include gases and solids as actual solvents. The metallographer and the geologist are beginning to speak of "solid solutions," a term which has cleared the atmosphere and opened the way toward a better understanding of matter in the solid state.

The terms "solid solution" and "crystalline solid solution" have both been used in referring to solids dissolved in solids. But the latter term is not as common, therefore the term "solid solution" will be used in this discussion.

[1] J. H. van't Hoff, "Solid Solutions," *Zeitschr. phys. Chem.*, V (1890), p. 322.

[2] As cited by J. V. Elsden, *Principles of Chemical Geology*, 1910, p. 116.

[3] J. L. R. Morgan, *The Elements of Physical Chemistry*, 1918, p. 147.

[4] Edward W. Washburn, *Principles of Physical Chemistry*, McGraw-Hill, 1915.

Solid solutions are frequently referred to as "mixed crystals," a term probably derived from a too literal translation of the German "Mischkrystalle." This translation is unfortunate since the term may suggest a merely mechanical mixture of crystalline substances like sand. As the term is liable to convey an entirely erroneous impression, it should be avoided in the interest of clearness.

> Owing to the restricted nature of molecular motion in crystals and the high viscosity of this state of aggregation, crystalline solutions in a state of equilibrium are seldom met with in practice, because the attainment of equilibrium in a reasonable length of time is so frequently prevented by the restraints upon the free movements of the molecules.[1]

This fact prevents satisfactory laboratory work on the problem. In geology we have at our disposal enormous lengths of time in which perfect equilibrium may be established, a factor, the importance of which is not always appreciated and which of course is rarely attained in the laboratory.

Although the writer is inclined to the view that the feldspars are aluminosilicates which in many cases are capable of forming solid solutions, nevertheless the usual nomenclature (ortho-, meta-, and trisilicates) will be employed without necessarily implying any particular theory of the chemical nature of these minerals.

ISOMORPHISM AND SOLID SOLUTION

Recognizing that isomorphous substances must be completely soluble in each other some mineralogists have come to the conclusion that the terms "isomorphism" and "solid solution" are synonymous. As this matter is of some importance here it will be discussed.

"The establishment of complete solid solution between the [plagioclase] feldspars raises the whole question of the use of the terms solid solution and isomorphism. Some authors use isomorphism to designate complete solid solution, others speak freely of limited isomorphism, and still others use the term in its original significance of simple crystallographic similarity."[2]

[1] E. W. Washburn, *Principles of Physical Chemistry*, 1915, p. 117.

[2] N. L. Bowen, *Amer. Jour. Sci.* (4), XXXV (1913), 595.

Hlawatsch,[1] in a very complete review, concludes that two minerals are isomorphous when: (1) they possess like crystal forms; (2) when their chemical composition is strictly analogous; (3) when they are capable of forming homogeneous "mixed crystals." The etymology of the term isomorphism strictly means "same form." We know, however, that two minerals that are isomorphous do not possess identically the same crystal form but differ from one another in many details. Though they are similar they are not identical. In addition to the crystallographic meaning of the term a similarity in chemical composition is implied. On the other hand in viewing such substances mineralographically the term is applied to systems where complete solubility in the solid condition exists among the components.

One of the difficulties in the correct use of these terms is illustrated by their application to the plagioclase feldspars. Albite is soluble in all proportions in anorthite; both of these minerals are triclinic but their formulas as generally written indicate respectively a trisilicate and an orthosilicate. Their mutual solubility has suggested to mineralogists that their chemical structures ought to be similar, being similar salts of the same acid as suggested by Schwantke[2] and Bayley[3]

But this gets us into an opposite difficulty. If the different salts are salts of the same acid, and have similar structures, how is it then that certain pairs are completely soluble while others are only partially so? To this question no direct answer is forthcoming, for "very little is yet known about the physical and chemical conditions which determine the solubility of a substance in a (liquid) solvent. In fact the essential nature of the process of solution must be regarded as at present uncertain. It has been noticed that solution is more likely to occur if the [components] are alike chemically, but no general rule can be framed."[4] On the other hand when we consider solids and (crystalline) solid

[1] Hlawatsch, *Zeitschr. für Kryst.*, Vol. LI (1912), pp. 417–91.

[2] A. Schwantke, "Die Beimischung von 'Ca' in Kalifeldspath und die Myrmekitbildung," *Centralbl. für min. Geol. und Pal.*, 1909, pp. 311–18.

[3] William S. Bayley, *Descriptive Mineralogy*, Appleton, 1917, 408.

[4] W. C. D. Whetham, *Theory of Solution*, Cambridge University Press (1902), p. 78.

solutions we find a more satisfactory answer to our query. Some fine work on this subject has been done by the Italians, especially by Ciamician and his co-workers.

Ciamician[1] and Bruni[2] have shown that single-ring organic compounds can form solid solutions only with other single-ring compounds. Thus, benzene (not benzine), Figure 1-(1), can form solid solutions only with such compounds as: thiophene, Figure 1-(2), pyrrol, Figure 1-(3), and pyridine, Figure 1-(4). In the same way a double-ring compound can only form a solid solution with another double-ring compound. Thus naphthalene, Figure 1-(5), only with quinoline, Figure 1-(6), etc. Under that same rule applied to triple-ring compounds anthracene, Figure 1-(7), forms solid solutions with its isomer, phenanthrene; with carbozol, Figure 1-(8), or with other triple-ring structures.

The complete solubility of one solid in another is more likely to occur if the chemical structure of each is similar. The similarity of the two, however, does not necessarily have to be so close as the term "isomorphism" would imply. For example some feldspars contain nephelite in solid solution, but this mineral cannot be regarded as isomorphous with the normal feldspar components. It does not seem unreasonable to assume that the mineralographic term "solid solution" is more comprehensive than the crystallographic term "isomorphism."

"It is convenient to regard . . . . [an isomorphous series] as formed by the replacement of one element or radical by another isomorphous with it, rather than as a mixture of different individual molecules."[3] It certainly is true that the term "replacement" is very commonly used, and no criticism to such use can be made provided that the conception of the solubilities of the components is not lost sight of, but there is danger of confusion in such cases. To the economic geologist the word "replacement" immediately suggests such phrases as "pyrite replaced by chalcocite" or "limestone replaced

[1] Ciamician, *Zeitschr. für Physt. Chem.*, XIII (1894), 1; XVIII (1894), 51; XLIV (1903), 505.

[2] G. Bruni, *Rendiconti dell' Accademia dei Lincei.*, Vol. VIII (1899), p. 570.

[3] A. J. Moses and C. L. Parsons, *Mineralogy, Crystallography, and Blowpipe Analysis*, 5th ed., 1916, p. 234.

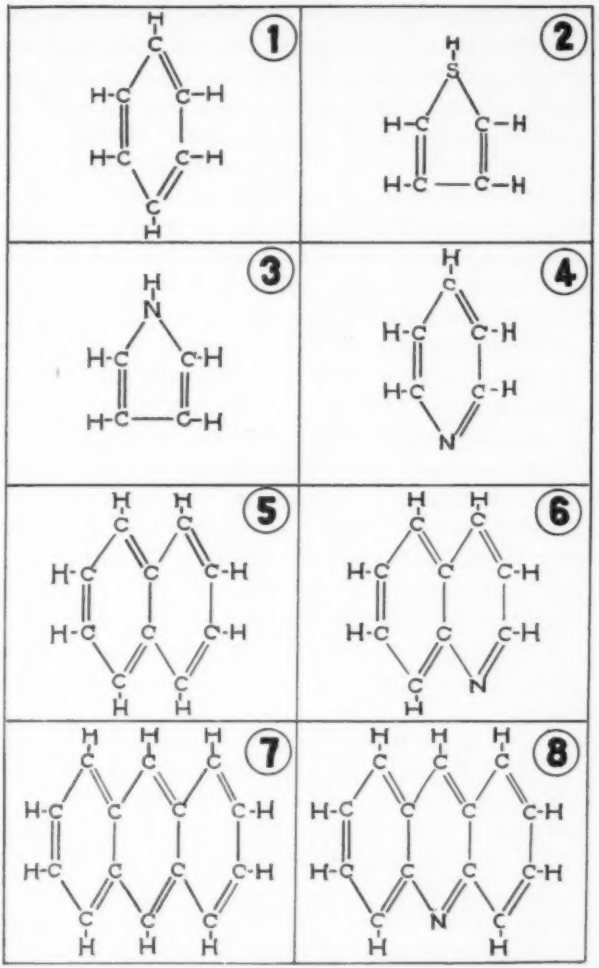


FIG. 1.—Structural chemical formulas of single-, double-, and triple-ring organic compounds, illustrating structures that form solid solutions. 1. Benzene. 2. Thiophene. 3. Pyrrol. 4. Pyridine. 5. Naphthalene. 6. Quinoline. 7. Anthracene. 8. Carbozol.

by ore" due to metasomatism. The term, however, is used in a very different sense by mineralogists. Is it chemically correct to speak of an element in a formula as "partially replaced" or "replaceable" by another? A replacement in a chemical sense means double decomposition taking place through chemical reaction, involving a thermal change; chemical reaction and thermal change being functions of each other. Thus if the potassium of orthoclase is "replaced" by sodium by chemical reaction then there should necessarily be a change in the thermal state of the system, the absorption or liberation of heat. While it cannot be stated positively that there is no change in the thermal state when liquid albite is added to liquid orthoclase at the same temperature, it seems more than likely that the albite will pass into solution without greatly disturbing the thermal equilibrium. The same principle probably applies to solid minerals, although it would be very difficult to prove it experimentally.

Of all the mineralogical systems studied up to the present time none is better known and understood than that of the plagioclase feldspars. It can be asserted with considerable emphasis that the variations in composition in the series are not due to chemical replacement but that they constitute a series of solid solutions. Moreover the plagioclase feldspars are not unique in nature, for many similar systems undoubtedly exist to which the same principle applies.

The reader should not overlook the fact that in this discussion of the feldspars we are dealing with them from the point of view which considers them solid solutions, and mixtures of solid solutions, and not "mixtures, admixtures, and mixed crystals" nor "molecules" which have certain portions "replaceable" by analogous units.

Thus the evidence that can be brought to bear upon this difficult problem points to the conclusion that $NaAlSi_3O_8$, when it exists as albite, and $CaAl_2Si_2O_8$ as anorthite probably possess similar structures. The suggestion of Bayley that the $NaAlSi_3O_8$ in orthoclase is barbierite (see later under "Feldspar Components") may be true but in view of the fact that other evidence points to a possible inversion of albite to barbierite (in the same way that orthoclase

probably changes to microcline) at temperatures below the freezing-point of any melt in the system, it does not seem very likely that the soda feldspar in a magma slowly cooling at great depths could take the form of barbierite. It is very likely that barbierite and microcline, when found, are usually not in their original form, but are the result of inversion, or transition.

The possible inversion of the potash and soda feldspars introduces a new element into the subject. Microscopic evidence does not seem to verify the supposition that microcline and barbierite are high-temperature forms, but rather that they are the result of inversion or that the presence of mineralizers has lowered the temperature of freezing below the inversion range of these minerals.

From the foregoing we conclude that orthoclase and albite have dissimilar structures, while barbierite and orthoclase possess similar atomic groupings. In an analogous way albite and microcline are probably alike.

FELDSPAR COMPONENTS

Modern textbooks on mineralogy list the following feldspars: (1) orthoclase, (2) microcline, (3) soda-orthoclase, (4) soda microcline, (5) anorthoclase, (6) albite, (7) oligoclase, (8) andesine, (9) labradorite, (10) bytownite, (11) anorthite, (12) plagioclase, (13) perthite, (14) celsian, (15) hyalophane, (16) carnegieite, and (17) anemousite. All the feldspars from orthoclase to and including perthite (1 to 13 inclusive) belong to a three-component system where the three units are: (1) potassium feldspar, (2) sodium feldspar, (3) calcium feldspar. Or if celsian, hyalophane, carnegieite, and anemousite be included then all the 17 members fit into a five-component system, of which the following are the components:

Type	Empirical Formula
Potassium Feldspar	$KAlSi_3O_8$
Sodium Feldspar	$NaAlSi_3O_8$
Calcium Feldspar	$CaAl_2Si_2O_8$
Barium Feldspar	$BaAl_2Si_2O_8$
Carnegieite	$Na_2Al_2Si_2O_8$

THE POTASSIUM COMPONENT

Orthoclase.—This mineral (ὄρθος, straight, and κλάς, angle), $KAlSi_3O_8$, is usually regarded as a salt of trisilicic acid, $H_4Si_3O_8$. In regard to its chemical composition *in nature* and its distinction from microcline we shall have more to say.

Microcline.—The name (μικρός, small, and κλίνειν, to incline) has reference to the fact that the angle (89°30′) between the two perfect cleavages differs but little from a right angle. Although the chemical formula of microcline is given as identical with that of orthoclase the petrographer usually has little difficulty in recognizing and separating it from orthoclase by the multiple pericline or "gridiron" twinning of the former as revealed by the microscope. Orthoclase either does not twin in this manner or does so on such an extremely fine scale as to be submicroscopic. Whether there is any physical or chemical difference between the two potash feldspars has been a matter of debate for some time. Investigators are divided between the two general theories; one group maintains that they are one and the same mineral, and differ from one another only in the magnitude of the twinning. On the contrary, another group maintains that there is a fundamental difference between the two minerals which although of identical composition possess different chemical structures.

Dimorphism of the Potassium Component.—"It appears highly probable that if the cross twinning and interpenetration of microcline become so minute as to be invisible under the microscope the crystals would be indistinguishable from those of orthoclase, and would, in fact, possess all the properties of that mineral. Many authors regard orthoclase as pseudo-symmetric; if this be so, all the feldspars may be in reality anorthic [triclinic]."[1]

According to E. Mallard and A. Michel-Lèvy it seems highly probable that orthoclase and microcline are not dimorphous, but identical, since they proved that the optical behavior of orthoclase would be a necessary consequence of an intimate multiple twinning of microcline lamellae after the albite and pericline law.[2]

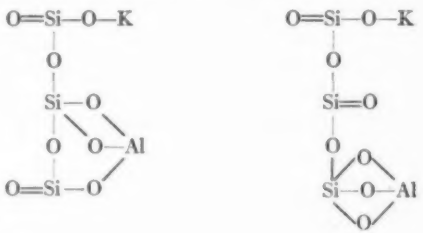
[1] H. A. Miers, *Mineralogy*, p. 460.

[2] Rosenbusch-Iddings, *Microscopic Physiography of the Rock-Forming Minerals*, p. 320.

On the other hand Vogt[1] speaks of the "probable occurrence of an inversion point in the potassic feldspar from an alpha to a beta modification, viz., from orthoclase to microcline." Barbier[2] has expressed the opinion that potash feldspar exists in two distinct forms which he regards as dimorphous, and which he says is a case of polymorphism. Assuming that there are two dimorphous forms it is not known whether the difference is due to "polymerism" or "isomerism." The term "polymerism" is applied where two compounds possess the same chemical composition but differ in their molecular weights.[3] For example, butyric acid, $C_4H_8O_2$, and aldehyde, C_2H_4O, differ by polymerism. On the other hand "isomerism" is used when two or more compounds possessing the same chemical composition differ in physical or chemical properties but have the same molecular weight, such as levulose and dextrose. If the difference between orthoclase and microcline is due to polymerism then the following formulae might express the relation:

$$(KAlSi_3O_8)n \qquad \text{and} \qquad (KAlSi_3O_8)\ (n+m)$$

where n and m are whole numbers. If the difference is due to isomerism then the kinship of the two minerals may be represented, as suggested by Clarke,[4] as follows:



[1] As cited by C. H. Warren, *Proc. Amer. Acad. Arts. Sci.*, LI, No. 3 (1915), p. 144.

[2] Ph. Barbier, "Researches sur la composition chemique de feldspaths potassique," *Bull. Soc. franç. minéral.*, XXXI (1908), 152–67.

[3] Since the examination of crystals by X-ray spectra has shown that our conception of molecules in solid matter has no real basis, it is well to bear in mind that such expressions as here used are subject to subsequent revision.

[4] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, p. 12.

The exact nature of the isomeric equivalences among the feldspars is not clear; they may be due to the structure of the salts independently of the acids they represent, or to isomerism among the acids themselves.[1]

Barbier sought to find distinct chemical differences between the two and suggested that the minerals may be distinguished by the fact that orthoclase often contains traces of lithium and rubidium while microcline does not seem to carry them. Boeke[2] pointed out that the two salts may have a selective solubility for these rarer alkalies, or that these control the magnitude of the twinning. But such a distinction is not fundamental as is shown by Vernadsky[3] when he found an unquestioned specimen of microcline from the Ilmen Mountains that contained rubidium to the extent of 3.13 per cent of Rb_2O.

It is generally stated by those who believe that there is no physical-chemical difference between orthoclase and microcline that the specific gravities of the two are identical. It is true that they closely approximate each other, as would be expected in the case of minerals so closely allied, but the slight differences are significant when definitely charted after careful analysis as is shown by the diagram, Figure 7, on page 231. Let us defer final conclusions on this argument till we come to its more detailed examination.

Another difference between the two minerals is the varying values of the indices of refraction. Weinschenk has stated it very clearly when he calls attention to the fact that orthoclase has lower indices of refraction in all crystallographic directions than anorthoclase, while those of microcline are a little lower in one direction and a trifle higher in others.[4]

Still another difference indicating a fundamental distinction between orthoclase and microcline is the thermal constants of these minerals as shown in Table I.[5]

[1] F. W. Clarke, "Constitution of the Natural Silicates," *U.S. Geol. Surv. Bull. 588*, p. 35.

[2] H. E. Boeke, *Grundlagen der Physikalisch-Chemischen Petrographie* (1915), p. 158.

[3] Vernadsky, *Bull. Soc. Min.*, Vol. XXXVI (1914), p. 258.

[4] Weinschenk-Clark, *Petrographic Methods* (1912), p. 330.

[5] D. M. Liddell, *Metallurgists' and Chemists' Handbook*, second ed., 1918, pp. 207–8; Joseph W. Richards, *Metallurgical Calculations*, 1918, p. 140.

If the figures are reliable there should be some basis for the opinion that the two similar minerals may be isomeric forms of the same substance.

TABLE I

Mineral	Melting-Point	Latent Heat of Fusion	Specific Heat
Orthoclase.....	1200°	100 cals.	0.1877
Microcline.....	1170°	83 cals.	0.197*

*See W. P. White, *Amer. Jour. Sci.* (4), Vol. XLVII (January, 1919), p. 17, for more modern values of the specific heat of microcline.

Harker says:

> If orthoclase and microcline are dimorphous, the latter must clearly be the lower [temperature] form. Where it occurs with the apparent characters of a primary mineral it is the latest product of crystallization and is characteristic of the most acid of granites and especially of pegmatites. . . . . The conversion of orthoclase to microcline, or the setting up of microcline structure in orthoclase, has been attributed to dynamic causes.[1]

Another explanation of the microclinic texture in potash feldspar is that it is solely due to stresses set up by dynamic forces and is not explained by the theory of dimorphism. Thus Rosenbusch[2] remarks:

> The fact that microcline is almost wholly confined to the older eruptive rocks which have been subjected to processes of faulting and pressure, together with the observation that normal orthoclase assumes the microstructure of microcline when it has experienced strong pressure, leads to the supposition that microcline-structure is a pressure phenomenon. The correctness of this assumption can be verified in many cases. The occurrence of crystals of microcline in cavities, however, proves that it has not been produced in this way in all cases. Still the absence of microcline from unaltered extrusives is notable.

The writer is fully aware that microclinic texture is frequently the result of dynamic stresses, but is inclined to the view that the stresses of dynamic metamorphism permit orthoclase, which is metastable at temperatures below its inversion point, to change to microcline. His conclusion is that pressure does not produce microcline from orthoclase; it only initiates and accelerates the change.

[1] Alfred Harker, *Natural History of Igneous Rocks* (1909), p. 259.

[2] Rosenbusch-Iddings, *Microscopical Physiography of Rock-Forming Minerals*, p. 320.

Working with thin sections and crushed fragments of the same specimen it was frequently observed that while the thin section showed the feldspar frequently twinned the crushed fragments of the same material were often untwinned. This applies to plagioclase as well as to the potash-soda varieties. In fact some "adularias" and "microclines" when examined in the form of thin plates (removed from the specimen by a knife blade) do not exhibit twinning while in thin sections of the same specimen the characteristic twinning is at once manifest. An excellent example of this phenomenon is the "microcline" from San Diego County, California. The suggestion is strong that sufficient pressure to develop twinning was present in the grinding process necessary for the preparation of the thin section. If soda orthoclase is metastable at normal temperatures then it follows theoretically that inversion to soda microcline would be hastened by heating. This proved to be the case. The San Diego County material was crushed, sieved, and sized, and then divided into four samples. One sample was not heated. No. 2 was heated one hour in a quartz glass crucible over a special Bunsen (Scimatco) burner. No. 3 was heated three hours, and No. 4, five hours. It was found that the percentage of the twinned fragments increased with the duration of heating. The significance of this simple experiment is the raising of the question whether thin sections can be relied upon uniformly as a means of proper identification of the feldspars.

The experimental work of Allen and Day[1] shows that the determination of the melting temperatures of the alkali feldspars and the thermal-reaction points indicative of inversions is extremely difficult. Working with natural microcline from Mitchell County, North Carolina, and employing "thermal apparatus . . . . sufficiently sensitive to detect any unsteadiness of a tenth of a degree [centigrade] with certainty, not the slightest trace of an absorption or release of heat was found." All such "phenomena appeared to be effectively veiled by some property [of the substance], presumably the viscosity." In natural magmas the presence of mineralizers "acting as solvents, keeps the minerals in a fluid condition until the temperature is far below that at which they would

[1] Allen and Day, *Carnegie Institute Pub. 31.*

otherwise solidify, thereby making possible their crystalline development."[1]

While it seems as if the matter cannot be definitely settled by laboratory work unless fluxes or high pressures are employed, yet the writer is of the opinion that microcline is an isomer of orthoclase. This implies that above the transformation temperature orthoclase is the stable mineral, while below it microcline is the normal form. If orthoclase passes this point on cooling without inverting, then the mineral exists in a metastable condition.

THE SODIUM COMPONENT

Albite.—Albite (*albus*, Latin for white) is the soda feldspar, $NaAlSi_3O_8$, which crystallizes in the triclinic or anorthic system. Structurally it can be represented by the same general formulas given above by substituting Na for K.

Barbierite.—It was not until recently that a monoclinic form of the soda component was even suspected. Barbier and Prost[2] found a sodium feldspar that is monoclinic and isomorphous with orthoclase, which Clarke[3] lists as "barbierite isomeric with albite." Schaller[4] says that the existence of a monoclinic soda feldspar isomorphous with orthoclase must be admitted. Thus we may have a relationship in the soda component identical with that prevailing in the potash feldspar. The thermal ranges of barbierite are unknown.

THE CALCIUM COMPONENT

Anorthite.—Anorthite (ἀν, not, and ὄρθος, straight) is a triclinic lime feldspar, but unlike the other components it is usually regarded as a salt of orthosilicic acid (H_4SiO_4) instead of the trisilicic. The formula is commonly written: $CaAl_2Si_2O_8$ or $CaAl_2(SiO_4)_2$.

So far as known no isomeric form of the lime component exists, consequently the term "lime component" and "anorthite" can be used indiscriminately.

The above three components, potash, soda, and lime, are the most important feldspar constituents. Two other components however ought to be mentioned.

[1] Weinschenk-Johannsen, *Fundamental Principles of Petrology*, 1916, p. 41.

[2] "Sur l'existence d'un feldspath sodique monoclinique isomorphe de l'orthoclase," *Bull. Soc. Chem.* (1908), III, 894.

[3] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, p. 35.

[4] *Bull. Soc. Min.*, XXXIII (1910), 320.

THE BARIUM COMPONENT

Celsian.—Celsian $BaAl_2Si_2O_8$ "is monoclinic and isomorphous with orthoclase."[1] No triclinic isomeric form of celsian is definitely known.

CARNEGIEITE

Our knowledge of carnegieite, $Na_2Al_2Si_2O_8$, the polymer of nephelite, has been derived almost entirely from the researches of the Geophysical Laboratory of the Carnegie Institution, although Thugutt[2] obtained crystals of it by rapidly cooling "nephelite hydrate." Carnegieite was first recognized as occurring in a cinder cone on the island of Linosa,[3] east of Tunis. It is "chemically, as well as physically, a feldspar, differing somewhat from those belonging to the orthoclase-albite-anorthite series. It may represent a member of a new series, containing variable amounts of carnegieite."[4] It has the same chemical composition as nephelite but it differs therefrom by dimorphism. It is triclinic and often twins polysynthetically after the albite law and less frequently after the pericline law. Carnegieite is reported as having a specific gravity of 2.571 at 25° C. The reader is referred elsewhere for more details, especially to Bowen.[5]

No better summary of the feldspar components can be offered than by giving a modification of a tabulation suggested by Washington.[6]

Fieldspar Group

$(R'AlSi_3O_8)$ $(R''\ Al_2Si_2O)_8$	Monoclinic-triclinic

"Adular" Subgroup

$(R'AlSi_3O_8)$	Monoclinic
Orthoclase	$KAlSi_3O_8$
Barbierite	$NaAlSi_3O_8$
Celsian	$BaAl_2Si_2O_8$

"Albite" Subgroup

$(R'AlSi_3O_8)$	triclinic
Microcline	$KAlSi_3O_8$
Albite	$NaAlSi_3O_8$
Anorthoclase	$(K,Na)AlSi_3O_8$

"Anorthite" Subgroup

$(R''Al_2Si_2O_8)$	triclinic
Anorthite	$CaAl_2Si_2O_8$
Carnegieite	$Na_2Al_2Si_2O_8$

[1] F. W. Clarke, *U.S. Geol. Surv. Bull. 588*, p. 35, 1914.

[2] S. J. Thugutt, *Neues Jahrb.*, Beilage Band 9 (1894), p. 561.

[3] H. S. Washington, *Jour. Geol.*, XVI (1908), 10; H. S. Washington and F. E. Wright, *Amer. Jour. Sci.* (4), XXVI (1908), 187, and XXIX (1910), 52–70.

[4] J. P. Iddings, *Rock Minerals* (1911), p. 243.

[5] N. L. Bowen, *Amer. Jour. Sci.* (4), XXXIII (1912), 551–73.

[6] H. S. Washington, "Suggestion for Mineral Nomenclature," *Amer. Jour. Sci.* (4), XXXIII (February, 1912), 149.

The method of approach here is the application of the phase rule to the feldspar system. The original presentation of the phase rule was garbed in mathematical terms. For the involved equations as set forth by Gibbs the thermo-equilibrium diagram has been substituted. To the metallographer the construction and interpretation of these diagrams present no great difficulties, but to the average geologist they are conventions that possess little or no meaning. As an understanding of the diagrams of the feldspar system is essential to what follows, a section at the end of the paper in the Appendix is introduced in which their construction and interpretation are discussed.

For most purposes it is sufficient to consider that the binary systems, soda-lime and potash-barium feldspars, constitute a series of solid solutions, the thermo-equilibrium diagrams of which are classified by Roozeboom as Type I. On the other hand the binaries, orthoclase-albite and orthoclase-anorthite, are represented by the eutectiferous type of diagram. Thus the feldspar binaries may be classified as follows:

	Isomorphous Type (Type I)	Limited Solubility Eutectiferous Type (Type V)
System	Soda-lime feldspars	Potash-soda feldspars
Name	Plagioclase series	Perthite series
System	Potash-barium feldspars	Potash-lime feldspars
Name	Hyalophane series	No name*

* The writer proposes on a later page the term "oranite."

TWO-COMPONENT SYSTEMS

THE SODA-LIME FELDSPARS—PLAGIOCLASE SERIES

The soda-lime feldspars or the plagioclase series is the best known isomorphous series in the mineralogy of the rock-forming minerals. Tschermak in 1864 propounded the theory that the plagioclase feldspars are isomorphous mixtures of albite and anorthite as is indicated by the formula: $m(NaAlSi_3O_8)+n(CaAl_2Si_2O_8)$. Vogt developed this theory, and established it from indirect evidence. It was experimentally demonstrated by the classical work

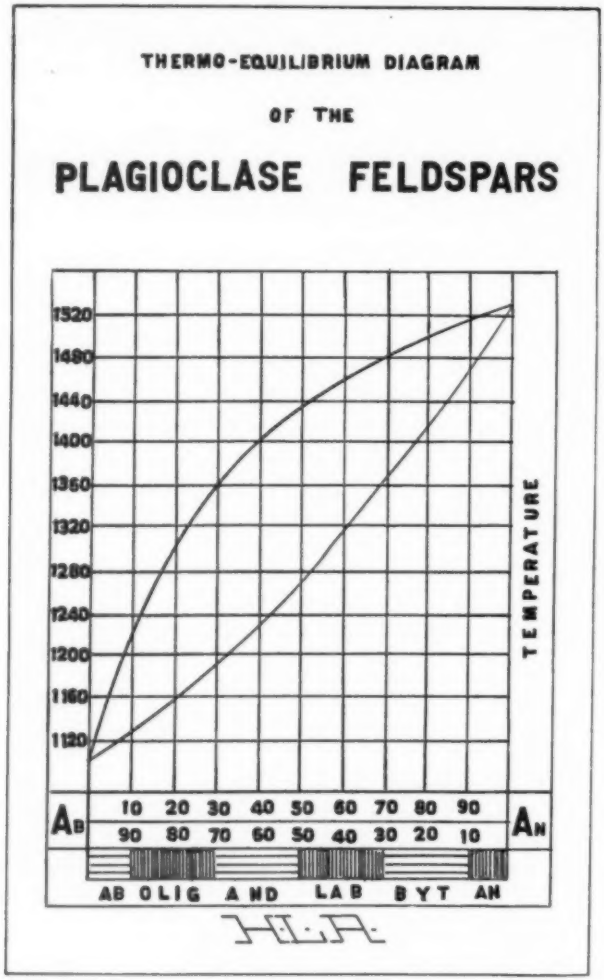


FIG. 2.—Thermo-equilibrium diagram of the plagioclase feldspars, based upon a molecular percentage (after Bowen).

of Allen and Day.[1] Figure 2 is the equilibrium diagram[2] of the soda-lime series, based upon a molecular percentage instead of a weight percentage as has been done in all the other diagrams.

The study of the solid-solution type of diagram shows us that the resulting crystals freezing from a mutual solution will not be homogeneous in composition, unless simultaneous or subsequent adjustment takes place, and consequently will vary in their optical properties as may be seen in zonal-grown crystals. But in deep-seated igneous rocks where the time of cooling is long, the non-homogeneous crystals gradually become uniform in composition by readjustment or exchange with each other and with the surrounding liquid. This process occurring between crystals is known as diffusion. All gradations between beautifully zoned plagioclase crystals and perfectly homogeneous ones occur in nature. The degree of homogeneity is therefore a function of the rate of chill, or, as the metallurgists would say, a measure of the rapidity of the quenching of the silicate alloy. Some zonal textures are, however, due to more complex processes such as the reabsorption of the margins of the already solid crystals and the adding of a new coating or layer deposited thereon. The writer believes that undue emphasis has been paid to the latter explanation of such textures and entertains the view that a large proportion of zonal crystals are not due to "magmatic corrosion," as it is called, but to normal magmatic crystallization under the influence of rapid chill.

Sometimes the crystal zones are sharply defined, each possessing fairly constant physical and chemical properties. These can be explained by irregularities in the rate of cooling.[3] The reversal of the order of zoning may be due to undercooling or the exposure of crystals to a liquid of a composition different from that of the one from which they crystallized.

The Properties of the Soda-Lime Feldspars.—It would seem as though our present knowledge of the physical properties of the plagioclase series was as complete as could be desired. Through

[1] A. L. Day and E. T. Allen, "The Isomorphism and Thermal Properties of the [Plagioclase] Feldspars," *Carnegie Inst. Pub. 31* (1905).

[2] N. L. Bowen, "Melting Phenomena of the Plagioclase Feldspars," *Amer. Jour. Sci.* (4), XXXV (1913), 583.

[3] N. L. Bowen, *Amer. Jour. Sci.* (4), XXXV (1913), 597.

the studies of Michel-Lèvy, Lacroix, Fouquè, Iddings, and many others, we have come to possess comprehensive data, more especially in regard to the optical properties. Under the circumstances it is

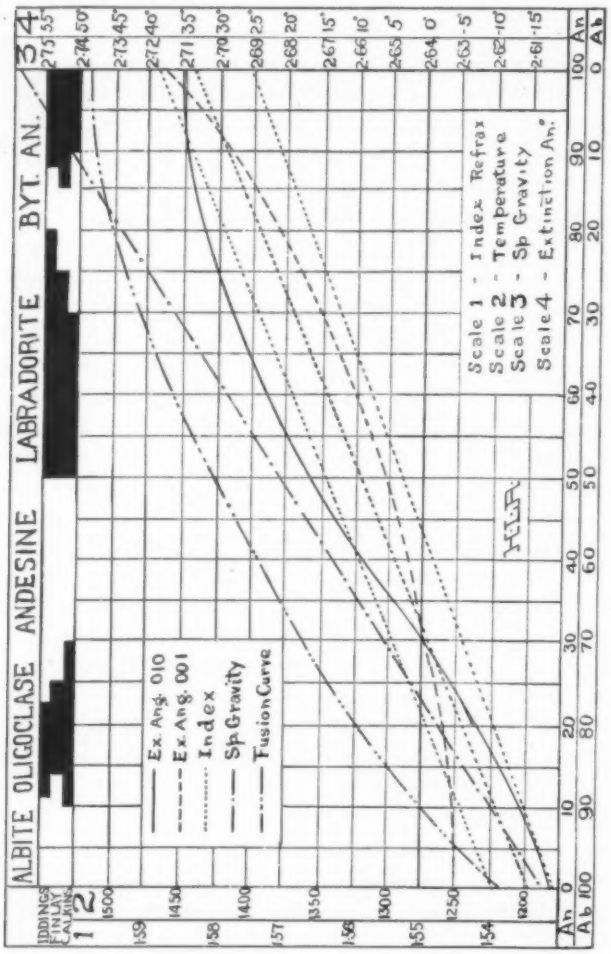

ALBITE OLIGOCLASE ANDESINE LABRADORITE BYT. AN.
IDDINGS FINLAY CALKINS
Ex. Ang. 010
Ex. Ang. 001
Index
Sp. Gravity
Fusion Curve
Scale 1 - Index Refrax
Scale 2 - Temperature
Scale 3 - Sp. Gravity
Scale 4 - Extinction An.°
An. 0 10 20 30 40 50 60 70 80 90 100 An
Ab. 100 90 80 70 60 50 40 30 20 10 0 Ab

FIG. 3.—Plot of the physical properties of the plagioclase feldspars, together with the liquidus curve of the thermo-equilibrium diagram. The classification of the series is shown at the top of the figure.

rather a surprising fact that very few authors correlate or show the relation between these optical and physical properties and their less-known thermal properties.

Groth[1] says that the physical properties of a completely isomorphous series "are continuous functions of their composition." In fact it may be safe to regard a binary system to be isomorphous from a knowledge of these physical curves alone even though the system has not been subject to thermal investigation. Thus for the plagioclase series we can draw the following curves: (1) specific gravity, which in case of artificial feldspars is a straight line, (2) indices of refraction, alpha, beta, and gamma values, and (3) extinction angles on the (010) and (001) crystallographic faces. Although these functions have long been known to petrographers it may be that their presentation in graphic form, as shown in Figure 3, demonstrates relationships which hitherto have not been sufficiently emphasized.

Classification of the Plagioclase Series.—The plagioclase series is classified into six subdivisions, albite, oligoclase, andesine, labradorite, bytownite, and anorthite. These subdivisions are not a random group of minerals with definite composition arbitrarily classified into a group but constitute a series of steps or gradation from one end member of the series, albite, to the other end member, anorthite, and consist of these end members in reasonably definite but differing proportions. There is, however, a lack of agreement among petrographers as to the limits of the variations that may occur in these subdivisions without altering the mineral names which have been assigned to them respectively. F. C. Calkins[2] has lessened the difficulty by suggesting a decimal standard of composition as a basis of classification. This method, adopted by the writer, gives the following proportions as applied to the members of this series. It will be noticed that each of the minerals varies within definite limits as to the percentage of the two constituents which it may contain without losing its identifying name.

Albite,	from Ab_{100} An_{0} to Ab_{90} An_{10}
Oligoclase,	from Ab_{90} An_{10} to Ab_{70} An_{30}
Andesine,	from Ab_{70} An_{30} to Ab_{50} An_{50}
Labradorite,	from Ab_{50} An_{50} to Ab_{30} An_{70}
Bytownite,	from Ab_{30} An_{70} to Ab_{10} An_{90}
Anorthite,	from Ab_{10} An_{90} to Ab_{0} An_{100}

[1] Paul Groth, *Chemical Crystallography* (1906), p. 96.

[2] F. C. Calkins, *Jour. Geol.*, XXV, 157–59.

It will be observed that the term "albite" is used in two senses: as a component of the system, that is pure $NaAlSi_3O_8$; and as a mineral capable of a range in composition within definite limits. All mineralogists, consciously or unconsciously, use this dual nomenclature: (1) albite as a component; (2) albite as a mineral found in nature; a distinction necessary to make. No modification of the classification limits of the plagioclase series can reduce these two uses to one. The metallographer has a similar problem. His components are metals, his solid solutions and definite chemical compounds are "meterals."[1] Meterals are strictly analogous to minerals. Consequently we see that in mineralogy there is no term corresponding to the metallographer's term "metal." There would be a distinct gain if we possessed a name for the components of a mineralogical system. The writer is using the word "minal" to convey the meaning here expressed. Thus there is albite as a minal, and albite as a mineral.

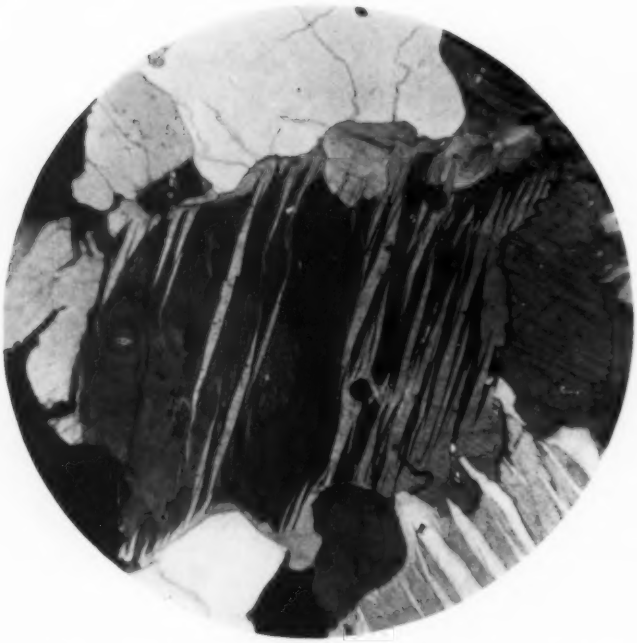
The theoretical percentages given above are based upon the assumption that the plagioclase series is a simple binary system. While such a conception is sufficient for most cases, a little study shows that natural specimens almost invariably contain some potash feldspar, the maximum being 10 to 12 per cent of the total in specimens near the albite end of the series, and decreasing as the percentage of anorthite increases. The potash component does not enter into the system in quite the same manner as the other two members for it is not a completely isomorphous component. Thus in classifying natural specimens one is compelled to consider the plagioclase series as a three-component rather than a two-component system.

Now the question arises what is the particular form of the potash feldspar which is found in the plagioclase feldspars? Miers[2] says

> since most of the plagioclase [feldspars] contain potash, we have to suppose either that monoclinic orthoclase can form [imperfect] isomorphous mixtures with triclinic plagioclase, or that the potassium feldspar is dimorphous, and that a modification exists belonging to the triclinic system and capable of entering into these mixtures.

[1] H. M. Howe, *Metallography of Steel and Cast Iron*, p. 232; Albert Sauveur, *Metallography and Heat Treatment of Iron and Steel*, pp. 293–94.

[2] H. A. Miers, *Mineralogy* (Macmillan, 1902), p. 452.



Microperthite (hyperperthite) in augite-syenite-granite, Ausable Forks, Clinton County, New York. Polarized light. ×50. Specimen 61.

Science & Industry
Department

The question is, is it orthoclase or microcline that occurs in plagioclase? We have learned from our discussion of isomorphism that it is probably microcline.

THE POTASH-SODA FELDSPARS—THE PERTHITE SERIES

Before the advent of Vogt's equilibrium diagram and Warren's masterful discussion of the potash-soda series it was held that this system was similar to if not identical with the plagioclase series; the two components being regarded as perfectly isomorphous.[1] But the Winchells[2] question this and say: "The close relation and gradation of optical properties corresponding to a gradation in chemical composition which exists in the plagioclase feldspars does not exist, or at least, has not been established, in the soda-potash feldspars." Harker[3] states that "we have to do with two . . . . interrupted series, Or-Ab, and Or-An, with a wide hiatus in the middle."

There would thus seem to be a hopeless difference of opinion regarding the potash-soda series. It will be shown later that these two extreme views are not as antagonistic as now appears.

Zapfee[4] is right when he says that "very little has been written regarding perthite, or perthitic intergrowth."

J. H. L. Vogt[5] was the first to give us an elaborate paper regarding the alkali feldspars, but his paper leaves many questions still obscure. Makinen[6] has studied the perthites from the pegmatites of Finland. But it has remained for Warren[7] to sum up the status of the perthite series and to discuss it quantitatively.

While the binary system, potash-soda feldspars, has not as yet been investigated thermally there seems but little doubt that

[1] P. Macnair, *Introduction to the Study of the Rocks and Guide to the Rock Collections in Kelvingrove Museum* (1911), p. 28; J. P. Iddings, "Obsidian Cliff, Yellowstone National Park," *U.S. Geol. Surv., Seventh Ann. Rept.*, pp. 269–70; A. H. Phillips, *Mineralogy* (1912), p. 408.

[2] N. H. and A. N. Winchell, *Elements of Optical Mineralogy*, p. 219.

[3] Alfred Harker, *Natural History of Igneous Rocks*, p. 244.

[4] Carl Zapfee, *Econ. Geol.*, VII, 137.

[5] J. H. L. Vogt, *Tschermak's mineral. und petrog. Mitt.* (1905), p. 24.

[6] E. Makinen, "Die Granitpegmatite von Tammela in Finnland," *Bull. d'l'Comm. Geol. de Finlande* (1913), pp. 1–101.

[7] Chas. H. Warren, *Proc. Amer. Acad. Arts. and Sci.*, LI (1915), 125–54.

it is of the general character shown in Figure 4 with the two components so regarded for the present only partially soluble in each other in the solid state, that it is a eutectiferous series. The first attempts to represent the diagram of the potash-soda feldspars were based upon the assumption that each component maintained uniform physical and chemical properties throughout heating and cooling. This assumption of course eliminated the possibility of their possessing dimorphous modifications. Consequently Vogt's diagram is extremely simple, and some of the lines are only approximate. Warren however suggested that the solubility lines should be drawn somewhat inclined instead of vertical as shown by Vogt. Harker illustrates by a diagram a eutectiferous system of which one component is dimorphous but did not apply it directly to the potash-soda feldspars. Warren stated the probability of the dimorphism of the potash component, orthoclase to microcline, and constructed his diagram with this in mind. Marc[1] has a different conception, which, although it possesses considerable merit, cannot be discussed in detail here. For the present we can derive considerable light upon the nature of the potash-soda feldspars by considering the diagram as given by Warren (Fig. 4).

In spite of the fact that the locations of the various points and the slopes of the curves of Warren's diagram are only approximate at the best it is believed that they are sufficiently accurate for our purpose. Warren has emphasized the truth that the two crystalline phases that make up perthitic intergrowths are solid solutions and not pure components. That is if we define orthoclase as pure $KAlSi_3O_8$ and albite as pure $NaAlSi_3O_8$ then the usual definition of perthite is not entirely satisfactory. Before the application of the phase rule to silicate systems the theory that the imbedded spindles had been introduced from without, subsequent to the solidification of the feldspar, could be regarded as plausible.[2] But today such an idea is abandoned by most workers in the field. In Figure 4 the composition of the original feldspar melt with an assumed value of 60 per cent K-feldspar and 40 per cent Na-feldspar is represented by the vertical line *NQC*. Now following

[1] Robert Marc, *Chemische Gleichgewichtslehre* (1911), p. 102.

[2] O. Wenglein, *Ing. Diss. Kiel*, 1903.

the method explained in the Appendix, the crystals will be found to have a composition of R through S toward A, as the temperature falls from T to T_2. The composition of the liquid on the other

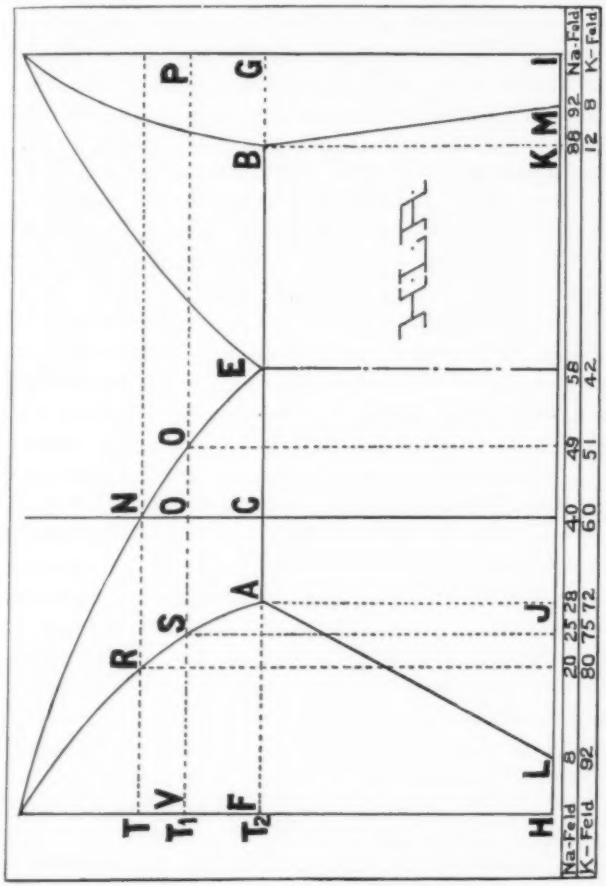


FIG. 4.—Thermo-equilibrium diagram of the potash-soda series, based upon a weight percentage (after Warren).

hand is indicated by the line *NOE*. Let us examine the crystal—a solid solution, which is of variable composition provided there is no readjustment taking place between the crystal phases and

the melt, each increment of which is in various degrees of saturation in respect to the sodium component. Then the phenomenon of diffusion (due to osmotic pressure) should take place tending to bring about a homogeneous mass. Let us suppose this diffusion takes place to completion while the temperature remains constant at T_2. A homogeneous solid solution nearly but not absolutely saturated with the sodium component results. We observe that the line AL is inclined, a fact which informs us that as the temperature falls the solubility likewise decreases. A temperature will soon be reached where saturation is complete. As "exsolution"[1] in solids is up to this point excessively slow, due to the high viscosity of that state, a condition of a supersaturation will occur. Assume that the feldspar is at normal temperature (*HLJKMI*), then in the course of geologic time this supersaturated crystalline mass will gradually separate into the two phases and give perthitic intergrowth. The perfect orientation of the crystal units in the host mineral would be maintained and hence we would expect to find that albitic phase "in irregularly lenticular layers . . . . in planes parallel to (801) or (100) and that both feldspars could have (010) in common."[2] This is probably the common form of perthite, due to exsolution of a supersaturated solid solution. As this is not a eutectic mixture it is well to be cautious in applying the term to all intergrowths found in rock sections. In fact many intergrowths that have the appearance of being eutectics may be due to secondary or subsequent processes. Whitehead[3] has emphasized this and illustrates the striking similarity in appearance between a true eutectic of 70 per cent of silver and 30 per cent of copper, and certain intergrowths which are found in sulphide

[1] There is no satisfactory word to express the phenomenon of the separation of two crystal phases due to supersaturation. "Precipitation" cannot be used as it designates a chemical relation; there is no chemical reaction taking place; it is merely a physical change. Warren uses the term "unmixing." This is not satisfactory for we are not dealing with original mixtures but with solutions. If we were observing a liquid solution we could say "crystallizes out of solution" but the homogeneous mass is already crystalline and such an expression would be unfortunate. It is really the opposite of "passing into solution," hence the term "exsolution" is proposed. The German term is "entmischung."

[2] J. P. Iddings, *Rock Minerals* (1911), p. 239.

[3] W. L. Whitehead, *Econ. Geol.*, XI, 1–13.

ores. His opinion is that the great majority of such intergrowths are due to secondary metasomatic replacement and not to the decrease in solubility of the components as they pass from the liquid to the solid phase. They are not eutectics in the sense in which the metallographer would use the term.

C. H. Smyth, Jr.,[1] says in regard to the microperthite contained in a "gneiss" from the Adirondack Mountains (which is, in all probability, the Adirondack augite-syenite of Algoman age):

> A very marked feature in a majority of the sections examined is the great abundance of the microperthite intergrowth of orthoclase and plagioclase. . . . . In most instances the microperthite has the appearance of that of a contemporaneous crystallization of the two feldspars; but enough sections contain absolute proof of its secondary nature to render it extremely probable that in this gneiss it is never an original intergrowth. Evidence of this secondary origin is seen in the plagioclase spindles passing unbroken across cracks in the orthoclase and in the evident optical continuity of the material of the spindles and secondary feldspar filling cavities and cracks adjacent to the microperthite.

Smyth gives the reader the impression that "contemporaneous crystallization of the two feldspars" and their "secondary origin" are incompatible. The writer would agree that the spindles could have formed subsequent to solidification and thus are secondary in this sense. Yet the material found in the two phases was present at the time the rock solidified. Smyth has apparently overlooked the question of the relative solubilities of the two phases with lowering temperature.

The examination of a large number of perthitic feldspars in thin section reveals the fact that most of them did not have an original eutectic composition, but have assumed their present form through the agency of exsolution. However, on the margins of the grains or in the interstitial spaces, perthite feldspars are frequently found, and are interpreted as representing the eutectic mixture. An excellent example of this type of feldspar is the pegmatite (graphic granite) from Bedford, New York.

Howe[2] makes the distinction between the eutectoid and the conglomerate of cementite (Fe_3C) and ferrite (alpha iron) in steels.

[1] C. H. Smyth, Jr., *Trans. New York Acad. Sci.*, XII (1893), 204.

[2] H. M. Howe, *Metallography of Steel and Cast Iron* (1916), pp. 71, 161.

The latter is the eutectic mixture. The eutectoid marks a change in the solid state and is called "pearlite," while the eutectic is referred to as "primary pearlite" or "ledeburite," a distinction well to make. The eutectoid pearlite is somewhat analogous to perthite due to exsolution. As this exsolution is a slow process the appearance of the two phases may not occur until many thousands of years after the freezing of the magma. There would be a gain for the sake of clearness if the literature of petrography can receive the term "perthoid" to refer to intergrowths of potash-soda feldspars due to exsolution, while "perthite" could be reserved for the true eutectic.

Undercooling.—Hitherto it has been assumed that each new phase made its appearance at the temperature at which it theoretically formed. In the laboratory this condition is rarely secured, while in nature, pressure, gases, and time are factors which profoundly affect the crystallization of a system. Inertia often causes a melt to remain in the liquid condition although the temperature may be below the freezing-point. This phenomenon is termed "undercooling."

The bridging of the eutectic gap by undercooling is discussed with the aid of the diagram shown in Figure 5. Three variables are represented: temperature, composition, and degree of equilibrium; and consequently a three-dimension model is necessary for representation. The back plane, $ABT_4\ ET_2$, is the normal diagram of the potash-soda feldspars, after Vogt and Warren. The plane nearest the reader is the metastable diagram when the two components A_x and B_x are completely soluble in the solid. The form assumed by the liquidus and solidus curves comes within Roozeboom's classification of Type III. The analogous points of the two diagrams are connected. The field of the rear plane where two solid phases are in equilibrium, *CDGOF*, becomes more and more restricted in passing to the front plane and comes to an end at E_1I. Stated in words, this indicates that the solubility of the two solid phases in each other becomes increasingly greater until complete solubility prevails. The converse of this is that if homogeneous crystals are formed upon freezing through the process of undercooling then because they are supersaturated in

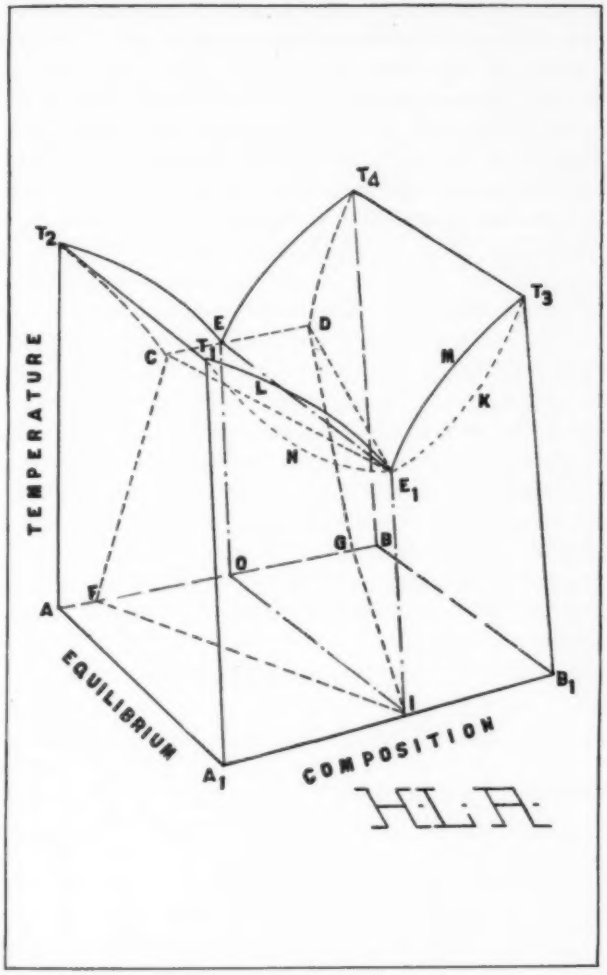


FIG. 5.—The stable thermo-equilibrium diagram of the potash-soda series after Warren, the back plane, the diagram for perthitic intergrowths and the metastable diagram, the front plane, for anorthoclase. The two diagrams are related through the degree of equilibrium.

respect to each other they will tend to separate into distinct and separate phases. The course of separation is indicated upon the basal plane of the diagram, by the lines *IF*, and *IG*, *F*, and *G* marking the limit. As a matter of fact we find in natural specimens every gradation between these two limits. That is, the diagram of one specimen may be properly represented by a cross-section of the solid model cut parallel with and near the back plane while another may be indicated by a section nearer to the front plane. It is obvious that the diagram, Figure 6, is highly diagrammatic and would be subject to modifications if the principle of dimorphism of the components were introduced.

Specific Gravities of the Potash-Soda Feldspars.—As has been noted before, Allen and Day have shown that the specific gravities of the plagioclase feldspars change uniformly from 2.605 for artificial albite, to 2.768 for artificial anorthite, the plot of their values assuming a straight line as in Figure 3. If, however, a break or cusp occurs in specific gravity curves it signifies a discontinuity in physical, crystallographic, and chemical properties, resulting from the development of new modifications or the formation of compounds. In the potash-soda series, the formation of compounds need not be considered, but the possible existence of dimorphous forms must be.

Hintze[1] gives the following data for the construction of such curves:

Mineral	Or-Ab Ratio	Percentage K_2O	Composition		Specific Gravity
			(A) Or Percentage	(B) K_2O Percentage	
Adularia.....	Or	16	100	95	2.56
Adularia.....	$Or_4\ Ab_1$	13	80	77	2.57
Amazonite.....	$Or_3\ Ab_2$	10	60	60	2.58
Perthite.....	$Or_1\ Ab_1$	7	50	41	2.60
Loxoclase.....	$Or_1\ Ab_4$	4	20	24	2.61

In graphic form these data are ambiguous. The differences can be clarified by the examination of another system which has been studied experimentally: that of $FeSO_4 \cdot 7H_2O$ and $MgSO_4 \cdot 7H_2O$.

[1] Carl Hintze, *Handbuch die Mineralogie*, II, p. 1358.

Regers[1] found that the ferrous salt, when pure, is monoclinic in crystal habit while the magnesium salt is orthorhombic.

> From aqueous solutions, at ordinary temperature it is possible to obtain . . . . [solid solutions] containing up to 54 per cent of magnesium sulphate, and possessing the monoclinic form of ferrous sulphate. There must, therefore, be a second (a monoclinic) form of magnesium sulphate, which can form [limited] isomorphous mixtures with ferrous sulphate. There is a gap between the mixture containing 54 per cent of the magnesium salt and the next higher one, which contains 81 per cent, no intermediate mixtures being known. Mixtures from this point up to pure magnesium sulphate exist, and they exhibit the orthorhombic form of the latter salt. If the densities of these various mixtures are plotted against the corresponding percentage composition, as in Figure 6, it is seen that the values lie upon separate and distinct straight lines, not parallel to each other.[2]

The gap referred to above undoubtedly implies a limited solubility between the components; that is, limited isodimorphism. It is strongly suspected that the potash-soda feldspars are of this type. If so Hintze's data can be treated in the manner shown in Figure 6. The upper of these two non-parallel lines represents gravities of the monoclinic modifications, or orthoclase-barbierite; the lower line the triclinic forms, microcline-albite. If Hintze's data can be relied upon, the lines in the figure strongly suggest the dimorphism of each component, for it is known that a dimorphous substance possesses different gravities depending upon its modification, and that the density of the higher temperature form is almost always higher than that of the lower. Consequently we would expect to find that orthoclase has a higher specific gravity than microcline. This is apparently the case. A factor, however, that may nullify the latter interpretation, is that natural specimens of orthoclase almost invariably contain more sodium feldspar dissolved in them than is contained in microcline. Since the gravity of the sodium component is higher than either orthoclase or microcline this would increase the gravity of natural specimens of orthoclase above that possessed by microcline irrespective of any dimorphism that may exist. Until laboratory experiments are undertaken final conclusions are impossible.

[1] Regers, Various articles in *Zeitschr. für Chem.*, 1889, 1890, and *Jour. C.S.*, 1891.

[2] Paul Groth, English translation of *Einleitung in die chemische Krystallographie, Chemical Crystallography* (1906), p. 92.

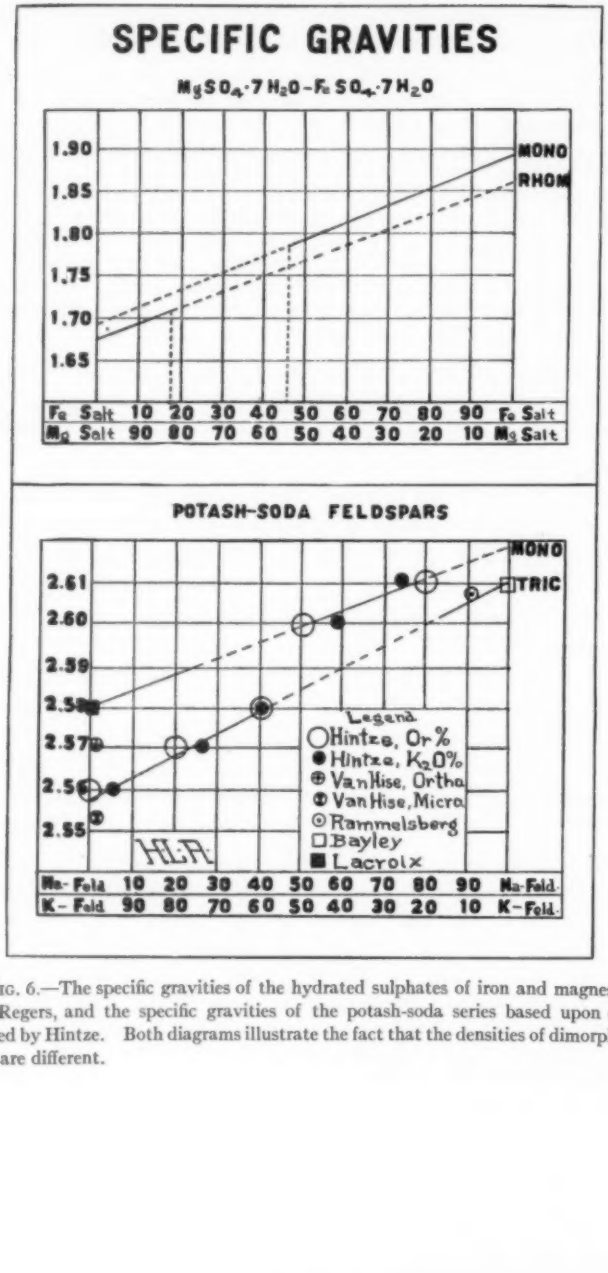


FIG. 6.—The specific gravities of the hydrated sulphates of iron and magnesium after Regers, and the specific gravities of the potash-soda series based upon data supplied by Hintze. Both diagrams illustrate the fact that the densities of dimorphous forms are different.

The Optical Properties of the Potash-Soda Feldspars.—It is a surprise, even to an experienced petrographer, that no adequate tabulation of the optical properties of the potash-soda series exists. What information there is in the literature is fragmentary and unrelated to the actual chemical composition. The writer has attempted to synthesize the data so given and has carried out sufficient microscopic examination of thin sections and crushed fragments to lead him to believe that it is possible to identify the subspecies of the potash-soda series with an accuracy approaching that obtained in the plagioclase feldspars.

Although the ease of distinguishing and identifying the different ranges in the plagioclase series is not duplicated in the potash-soda series, yet the maximum extinction angles on the (010) and (001) faces appear to offer fairly reliable criteria. In most text-books on optical mineralogy the extinction angles for orthoclase on the (001) and on the (010) faces are given as 0°, and 4°30′ to 5°, respectively. As most, if not all, natural orthoclase contains some sodium feldspar in solution, the angular value for the pure substance is perhaps a little lower than the last named. As the amount of the sodium component increases to about 25 per cent the extinction angles on the (010) face increase from 5° to about 12° while the (001) extinction angle changes from zero to about 3°. In the form of crushed fragments this test becomes a simple though not a quick method of determination. A similar relation exists for microcline and soda microcline. The extinction angle on the (001) face is slightly less than 15° for nearly pure material but becomes 17° to 18° with increased soda content; likewise the (010) face extinction increases from 4°30′ to nearly 10°.

Potash albite is usually distinguished by the fine albite twinning, although this may be replaced by fine microclinic twinning instead, or no twinning may appear at all even under high magnifications, and reliance upon the extinction angles from cleavage faces must be substituted. The extinctions on the (001) face are about 5° and on the (010) face about 10°. With increasing soda content pure albite is reached when 21° on the (010) is found. The great difficulty is in distinguishing by extinctions alone saturated (or supersaturated) soda orthoclase from potash albite

containing its maximum amount of the potash component, but recourse to indices of refraction furnishes a fairly accurate means. The optical mineralogy of this system should be studied in conjunction with the chemical analyses, which for convenience should be recast in terms of the three components.

It is chiefly from the examination of some sixty specimens of natural potash-soda feldspars that the writer offers the diagrams (shown in Fig. 7) of the extinction angles of the potash-soda series. They are tentative and suggestive, nothing more. The dimorphism of the sodium component is not represented; for no information is at hand. Consequently barbierite has been left out of consideration.

Some of the uncertainty about the accuracy of the curves is because of the degree to which the lime component affects the extinctions. All of the specimens examined contained anorthite in solution up to 10 or 15 per cent of the whole and the problem was to correct the extinctions for the simple binary. The extinction angles of the plagioclase series, together with those of the potash-soda feldspars, whose chemical composition was known,[1] enabled the writer to plot equal extinction contours (isogonic lines) for that portion of the ternary system (K-, Na-, and Ca-feldspars) represented by natural specimens. These in turn made it possible to draw the extinction curves for the pure binary system.

Classification of the Potash-Soda Series.—Most mineralogists recognize that orthoclase usually contains an appreciable amount of soda, and that albite carries some potash. Winchell,[2] for example, gives orthoclase, $KAlSi_3O_8$; soda orthoclase, $(K,Na)AlSi_3O_8$; albite, $NaAlSi_3O_8$; and anorthoclase, $(Na,K)AlSi_3O_8$. While these expressions in general convey fairly definite meanings, it is well to remember that there is no definite ratio between the K and Na in homogeneous crystals which are members of the series, and that no single chemical formula can be given for them. Such feldspars with the potash and soda components in appreciable amounts should be considered as solid solutions limited to certain

[1] Dana, *System of Mineralogy*, sixth ed. (1892), p. 324.

[2] N. H. and A. N. Winchell, *Optical Mineralogy* (1909), p. 219.

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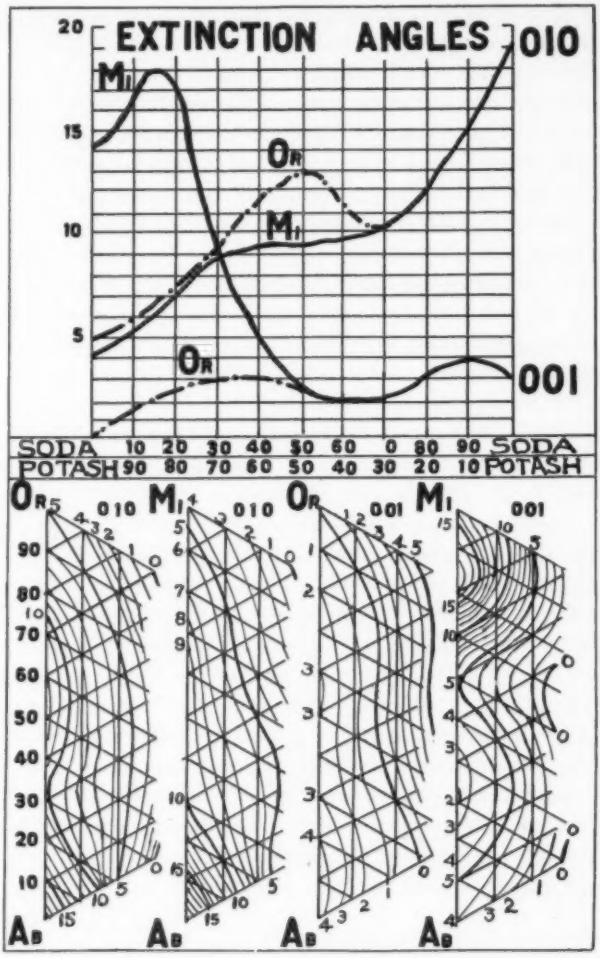

FIG. 7.—Extinction angles of the potash-soda series. The upper diagram shows values of the extinctions for the simple binaries, microcline, Mi; albite, Ab; and orthoclase, Or; albite, Ab, on the two faces, (010) and (001). The lower diagram shows the alkalic portions of the ternary diagram, K-, Na-, Ca-feldspars. The values of the extinction angles are shown by isogenic lines. Both diagrams are tentative.

ranges of composition. In general the term "soda orthoclase" is clear in its meaning.

Rogers[1] points out a danger in employing the term soda orthoclase in that it is somewhat ambiguous, for "soda-orthoclase may mean an orthoclase in which a portion of the potassium is replaced[2] by sodium or it may mean that sodium compound corresponding to orthoclase." For the latter it is better "to use a distinctive name for the monoclinic feldspar in which sodium predominates molecularly[3] over potassium." For such a mineral the term barbierite has been proposed. The writer fully appreciates the necessity for such distinctions, and maintains that soda orthoclase should mean an orthoclasic feldspar with some sodium component dissolved in it (Winchell's $[K,Na]AlSi_3O_8$) while sodium orthoclase should refer to barbierite.

The limits of the range here proposed for soda orthoclase are K-feldspar 90, Na-feldspar 10, to K-feldspar 70, Na-feldspar 30.

There exists considerable uncertainty regarding the composition of anorthoclase. Rosenbusch[4] gives as the range of this mineral the following ratios: Na-feldspar 67, K-feldspar 33-Na-feldspar 82, K-feldspar 18. These ratios suggest that anorthoclase is analogous to soda orthoclase, that is, it is a feldspar consisting chiefly of the sodium component with an appreciable amount of potash feldspar dissolved in it. Yet a study of the available chemical analyses of "anorthoclase" would suggest that these limits should be extended farther toward the potash side of the diagram, embracing in many cases the range where, under equilibrium conditions, perthite occurs. It is quite reasonable therefore to consider that many anorthoclases are undercooled metastable solid solutions of the two alkali components. A clear

[1] A. F. Rogers, "The Nomenclature of Minerals," *Proc. Amer. Phil. Soc.*, LII (1913), 610.

[2] It is well to recall the objection to an expression of this kind.

"Replaced" is unsatisfactory in a physical-chemical sense.

Professor Johannsen informs me that he has used "proxied by" instead of "replaced by." There is no misunderstanding of that term.

[3] The application of X-rays to crystal structure has shown that molecules do not exist as such in solids.

[4] Rosenbusch-Iddings, *Microscopic Physiography of the Rock-Forming Minerals*, p. 340.

conception, such as this, seems necessary to supplant the present nomenclature which is very unsatisfactory due to its indefiniteness.

The question arises whether it is best to restrict "anorthoclase" to the central portion of the equilibrium diagram and to undercooled homogeneous crystals of perthitic composition, or to limit it to albitic feldspars containing the potash component up to a maximum of 20 per cent. After due consideration the former proposal is the one here adopted. The average of the 47 available analyses of this mineral is higher than 20 per cent in the potash component and is therefore within the perthitic range.

If the term "soda orthoclase" is used for that portion of the potash-soda series indicated by the range $Or_{90}Ab_{10}$-$Or_{70}Ab_{30}$ and the term "anorthoclase" for the range in the center of the equilibrium diagram, then it is necessary to supply a term for albitic feldspars containing the potash component up to 20 per cent. For this range of solid solutions, K-feldspar 20, Na-feldspar 80- K-feldspar 5, Na-feldspar 95, the term "potash albite" is proposed.

Anorthoclase is here used as the name to designate the range, K-feldspar 70, Na-feldspar 30- K-feldspar 20, Na-feldspar 80, when it is a supersaturated undercooled metastable homogeneous solid solution, potentially perthite, through the intermediate stages of cryptoperthite and microperthite.

The emphasis that mineralogists place upon the distinction between monoclinic and triclinic crystals has resulted in considerable confusion about the distinction between soda orthoclase, anorthoclase, and soda microcline. For example, the interesting classification of Klockmann[1] will illustrate this point:

Formula	Monoclinic		Triclinic	
	Component*	Isomorphous Mixture	Component*	Isomorphous Mixture
$KAlSi_3O_8$....	Orthoclase	Soda Orthoclase	Microcline	Anorthoclase
$NaAlSi_3O_8$...	Unknown†		Albite	
$CaAl_2Si_2O_8$...	Unknown	.....	Anorthite	Plagioclase

* Free translation of "Selbständig."

† For this modification of the sodium component the term barbierite has been proposed.

[1] Klockmann, *Lehrbuch der Mineralogie* (1912), p. 488.

He furthermore puts in parentheses after "anorthoclase," "soda microcline"[1] and "microcline albite."[2] A similar procedure is followed by Iddings[3] who speaks of the potash-soda feldspars rich in soda as "soda microcline (anorthoclase)."

It seems to the writer that this confusion is due to the failure to recognize the possible dimorphism of each of the components in the series, that is, there may be two distinct binary systems in one: the so-called monoclinic series with orthoclase and barbierite as end members, and the triclinic potash-soda feldspars with microcline and albite as components. If this is recognized then it is logical that the two should be classified as follows:

Monoclinic: Orthoclase, soda orthoclase, monoclinic anorthoclase, potash barbierite, and barbierite.

Triclinic: Microcline, soda microcline, triclinic anorthoclase, potash albite, and albite. The interrelationship that exists between the monoclinic and triclinic anorthoclases has been pointed out by Dana[4] who says that the axial angle of anorthoclase varies with the temperature, "becoming monoclinic in optical symmetry between 86° and 264° C. but again triclinic on cooling. This is true of those containing a little calcium" (anorthite). Although the writer is somewhat cautious in proposing new terms—for the literature of mineralogy and petrography is already burdened with many useless names, some of which are worse than useless—yet there has been no systematic attempt to subdivide the potash-soda series into definite ranges analogous to oligoclase, andesine, labradorite, etc. Calkins' decimal principle as applied to the plagioclase series is so logical that its application to the potash-soda series is worth attempting.

The terms hypoperthite and hyperperthite may appear strange to the petrographer but the metallographer will recognize old friends. The nomenclature proposed is an adaptation of the terms hypoeutectoid and hypereutectoid as applied to steels. The word eutectoperthite is self-explanatory. If such refinement in classifying the system is neither possible nor desirable, then perthite can

[1] Natronmikroklin. [2] Mikroklinalbite.

[3] Joseph P. Iddings, *Rock Minerals*, 1911, p. 235.

[4] James D. Dana, *System of Mineralogy*, sixth ed., 1892, p. 324.

be substituted for the three names in the center of the table as is indicated at the sides.

Monoclinic		Ratios	Triclinic	
	Orthoclase	$Or_{100}Ab_0$ -$Or_{90}Ab_{10}$	Microcline	
	Soda orthoclase	$Or_{90}Ab_{10}$ -$Or_{70}Ab_{30}$	Soda microcline	
Perthite (stable) Anorthoclase (metastable)	Hypoperthite	$Or_{70}Ab_{30}$ -$Or_{45}Ab_{55}$	Hypo-perthite	Perthite (stable)
	Eutectoperthite	$Or_{45}Ab_{55}$ -$Or_{35}Ab_{65}$	Eutecto-perthite	Anorthoclase (metastable)
	Hyperthite	$Or_{35}Ab_{65}$ -$Or_{20}Ab_{80}$	Hyperthite	
	Potash barbierite	$Or_{20}Ab_{80}$ -Or_5Ab_{95}	Potash albite	
	Barbierite	Or_5Ab_{95} -Or_0Ab_{100}	Albite	

Some criticism may arise in that the above classification is more detailed than is warranted by the determinations possible with the petrographic microscope upon natural specimens. The writer feels, however, that with greater care and proper emphasis, microscopic distinctions are possible that will approach the accuracy now obtainable in classifying the soda-lime series.

THE POTASH-LIME FELDSPARS—"ORANITE" SERIES

One of the strange facts of mineralogy is that the potash-lime feldspars are considered rare in nature, and are little discussed in the literature. Harker[1] says "the relation between orthoclase and anorthite are doubtless of the same general kind [orthoclase-albite], though the higher melting-point of the latter mineral will presumably throw the eutectic point somewhat nearer to orthoclase." Bayley[2] remarks that "mixtures of the potash and calcium molecules[3] are extremely rare as minerals, but that they have been formed experimentally in the laboratory." All available data lead us to conclude that the $KAlSi_3O_8$-$CaAl_2Si_2O_8$ system is similar to the potash-soda series, except that we do not have to consider an isomeric modification of anorthite, which reduces the system to one of less complexity. The eutectic temperature is probably higher and the lines of solubilities are nearer to the sides of the diagram.

[1] Alfred Harker, *Natural History of Igneous Rocks*, p. 246.

[2] Wm. S. Bayley, *Descriptive Mineralogy*, 1917, p. 408.

[3] "Components" is to be preferred for reasons already given.

The reason why it is rare in nature is not far to seek; a rock high in potash and lime but low in soda is rare, and when found the two feldspathic phases occur as separate and distinct grains. This can be explained on the basis that melts of the potash-lime feldspars, especially when rich in the latter component, are much less viscous than the potash-soda ranges. Consequently their separation into distinct identities is much more common, and intergrowths are rare. That the latter do occur, however, the writer feels convinced.

In the Adirondack Mountains the anorthosite and the augite syenite, both of Algoman age,[1] occur in igneous contact with each other with such field relations as to indicate that certain batholithic masses of these two rocks invaded the country rocks (chiefly Grenville sediments) at about the same time, although the anorthosite is probably the older of the two in all cases. Magmatic assimilation of the syenite by the anorthosite has taken place to some extent in zones where they adjoin one another. The feldspar of the syenite is microperthite (antiperthite) (hyperperthite) while that of the anorthosite is acid labradorite ($Ab_{55}An_{40}Or_5$). In the syntectic rock, marking the zone of contact, microscopic examination reveals intergrowths of potassic feldspar and labradorite or orthoclase with an appreciable amount of lime ("lime-orthoclase") holding blebs of either labradorite or bytownite. It is obvious that such rocks are not "typical" and that the process of the development of these potash-lime feldspars is more involved than the simple freezing of a magma and consequently these cannot be pointed to as good examples of this rather neglected family.

But to return to more normal rocks, we find that the feldspathic content of most granites, syenites, monzonites, etc., is not limited to one species of feldspar. Even a hasty petrographic study of slides of these rocks shows "orthoclase and plagioclase." In the monzonites and granodiorites both alkali and plagioclase feldspars are present. Occasionally a basic representative of these carries in addition to the potassic or alkali feldspars, basic plagioclase,

[1] H. L. Alling, "Some Problems of the Adirondack Pre-Cambrian," *Amer. Jour. Sci.* (4), XLVIII (July, 1919), 62; "Geology of the Lake Clear Region," *N.Y. State Mus. Bull. 207–8* (1919), pp. 119–20.

Science & Industry
Department

labradorite, or even bytownite. In such rocks the feldspars are undoubtedly approaching, as a limit, the potash-lime binary system. The infrequency of intergrowths of these feldspars is the cause of the failure to recognize the system in nature.

Referring to the triangular plot of the feldspar analyses (see Fig. 19), it will be seen that a few specimens called "labradorite" and "anorthite" are approaching the side of the triangle occupied by the potash-lime feldspars.

The lack of specimens of this binary system prevents any accurate attempts being made to outline or to plot the physical and optical properties. They may, however, be inferred. The specific-gravity curves are steeply inclined, extending from 2.58 for orthoclase to 2.765 for anorthite. The gravity line for microcline and soda-microcline probably does not reach the high lime ranges, and ends somewhere between the two limits. The indices of refraction likewise are more inclined. In the center of the diagram, these lines have no practical significance, as undercooled metastable crystals of analogous to anorthoclase are probably unknown or very rare in normal rocks.

When we come to the nomenclature and classification of the binary, we enter virgin fields. What name shall be applied to the intergrowths described above as occurring in the Adirondacks? Shall perthite be used? There is considerable objection to such a practice; it would be extending the meaning of a well-established term and the modern tendency is in the opposite direction. Rogers[1] has proposed a slight extension of the term perthite to include intergrowths of two alkali feldspars when the orientation of the blebs differs from the customary relation. This implies that a certain element of textural habit is associated with the compositional significance. All of this leads to the obvious conclusion that a new word is required. The writer proposes, for intergrowths of potassic and high lime plagioclase feldspars, either eutectics or due to exsolution, the term "oranite." Its derivation tells the composition: *or*thoclase-*an*orthite—*ite*, the mineralogical ending. The same name can include intergrowths of soda microcline and potash anorthite.

[1] A. F. Rogers, *Jour. Geol.*, XXI (1913), pp. 202–7.

It will be seen that in order to limit the feldspar species to definite areas in a three-component ternary diagram the potash-lime series must be classified, in analogous fashion, to that already proposed for the soda-lime and potash-soda binaries. For feldspars of the K-Ca series, analogous to soda orthoclase and potash albite, the terms "lime orthoclase" and "potash anorthite," respectively, are suggested as meeting the present requirements.

THE BARIUM-POTASH FELDSPARS—HYALOPHANE SERIES

The name hyalophane is said to have been proposed by Waltershausen in 1855[1] from the Greek, ὕαλος, "glass," and φαινεσθαι, "to appear," alluding to its transparency. It is described as a barium-bearing feldspar found in transparent crystals similar to adularia. It is exceedingly rare in nature, the most famous locality being in the white dolomite of Binnenthal, where it was formed as the result of igneous contact action.

The melting-point of celsian is not known, and furthermore very few suggestions have been found in the literature that would indicate the probable nature of the thermo-equilibrium diagram. Iddings gives: $m(KAlSi_3O_8)$, $n(BaAl_2Si_2O_8)$, suggesting isomorphism similar to that possessed by the plagioclase series. Winchell gives a plot of the indices of refraction which incline toward higher values with increasing barium content, which is strictly analogous to the plagioclase system. Iddings supplies data for the construction of the specific-gravity curve, which takes the form of a straight line. Clarke[2] quotes the opinion of Standmark[3] that "the mineral celsian . . . . is monoclinic and isomorphous with orthoclase." Klockmann[4] likewise expresses the same view. In speaking of hyalophane in a more restricted sense, Clarke says: "Hyalophane and other barium feldspars are mixtures of orthoclase and celsian." In consistence with this view both Winchell and Iddings employ symbols and ratios which show a continuous range from Or to Cn, as follows: $Or_{19}Cn_1$, $Or_{10}Cn_1$, Or_4Cn_1, Or_3Cn_1, Or_7Cn_3, and Cn (Fig. 8).

[1] W. S. Waltershausen, *Pogg. Ann.*, XCIV, 134.

[2] F. W. Clarke, *U.S. Geol. Surv. Bull. 588* (1914), p. 35.

[3] Standmark, *Zeitschr. für Kryst. und Min.*, Vol. XL (1907), p. 89.

[4] Klockmann, "Isomorphe mischung von $K_2Al_2Si_6O_{16}$ mit $BaAl_2Si_2O_8$," *Lehrbuch der Mineralogie* (1912).

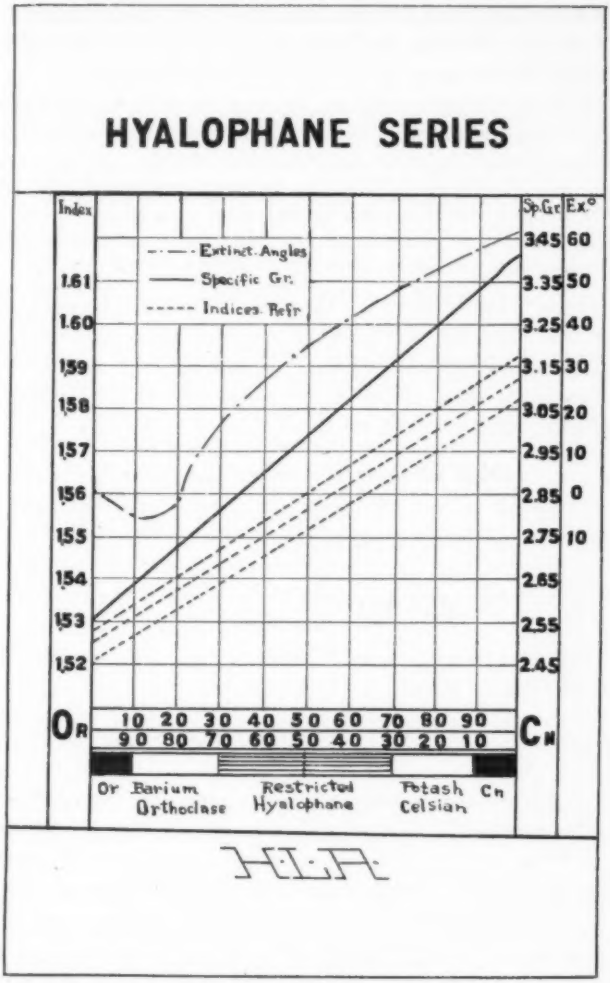

FIG. 8.—Plot of the physical properties of the hyalophane series. The uniform character of the curves implies that the orthoclase celsian system is a series of solid solutions, and that no chemical compound exists between the components. Data taken from Iddings and Winchell.

On the other hand the conception of a definite chemical compound within the series has been expressed by a number of mineralogists. Miers[1] says

> hyalophane corresponds to the formula $K_2BaAl_4Si_8O_{24}$ (not isomorphous [K_2,Ba]) and this can be expressed as a mixture of $BaAl_2Si_2O_8$ with 2 ($KAlSi_3O_8$), i.e., as compounded of two molecules of orthoclase with one molecule of barium silicate similar to anorthite. This union is exactly analogous to the mixture of albite and anorthite in the (plagioclase) group . . . . but in hyalophane the mixture appears to be only in one definite proportion, so that the mineral is to be regarded as a double salt rather than a solid solution.

A similar view is taken by Moses and Parsons[2] who give hyalophane the following formula: $(K_2,Ba)Al_2(SiO_3)_4$ as though the fundamental acid was metasilicic. Let us see how such an interpretation is possible. If we employ one unit of the barium and two of the potash components then

$$2\times(KAlSi_3O_8)=K_2Al_2Si_6O_{16}, \text{ a trisilicate}$$

$$\frac{BaAl_2Si_2O_8}{K_2BaAl_4Si_8O_{24}}, \text{ an orthosilicate.}$$

Now

$$\frac{K_2BaAl_4Si_8O_{24}}{8}=K_2BaAl_4(SiO_3)_8.$$

And furthermore

$$\frac{K_2BaAl_4(SiO_3)_8}{2}=(K_2Ba)Al_2(SiO_3)_4,$$

which looks like a metasilicate but it may be far from being one. By taking two trisilicate units and one orthosilicate unit we get the result. The writer must take exception to such an interpretation. Furthermore Moses and Parsons indicate by the comma between the K_2 and Ba that the ratio between them is not constant. In other words the ratio of the number of units of the two components varies. If it varies then the so-called formula would be much more complex and depart from the form assumed by a metasilicate.

[1] H. A. Miers, *Mineralogy*, p. 461.

[2] A. J. Moses and C. L. Parsons, *Mineralogy, Crystallography, and Blowpipe Analysis*, fifth ed., p. 493, 1916.

Their formula, upon the basis that the end members are orthoclase and celsian, is misleading.

Groth[1] discusses the difficulty of distinguishing between isomorphous "mixtures" and compounds when there appears to be a definite and fixed ratio between the end members of a given series. In referring to the "triclinic feldspars" [plagioclase?] he says:

> The predilection toward certain definite mixture ratios in the series named is probably connected with the fact that apparently a regular distribution of the two kinds of atomic groups provides a particularly stable equilibrium of the crystal structure, since it occurs also with isomorphous substances of completely analogous chemical constitution.[2]

The fact that many "isomorphous mixtures [occur] in simple stoichiometric proportions appear in certain cases to possess greater stability than do those in other proportions." The modern "view of crystal structure . . . . shows . . . . that the formation of a crystal from two different kinds of chemical molecules,[3] even though these differ very slightly from each other, will give a particularly stable structure when the molecules[3] take part in this formation in regularly alternating manner; since such a substance has as much right to the name of 'molecular compound' as to that of 'isomorphous mixture,' it is evident that that view does not permit of any sharp boundary between the two ideas."[4]

Groth points out the inherent failure of the usual mineralogical methods of attack to distinguish compounds from isomorphous mixtures, solid solutions. Upon such problems mineralography sheds considerable light. Unless a compound is unstable at its melting temperature, the *liquidus* curve assumes a maximum in the form of an arch. In all cases there is an abrupt change in the direction and slope of the curves showing the physical properties of the series. This is clearly emphasized by the $CaSiO_3$-$MgSiO_3$ (Pseudowollastonite-Clinoenstatite) diagram.[5] Both of the end members of the series form eutectiferous mixtures with the common double salt, diopside. If the specific-gravity curve is plotted

[1] P. Groth, *Chemical Crystallography*, translation by H. Marshall, 1906, p. 98.

[2] P. Groth. *Neues Jahrb. f. Mineral.*, II (1903), 93 ff.

[3] Components. [4] P. Groth, *Chemical Crystallography* (1906), p. 105.

[5] Allen and White, *Amer. Jour. Sci.* (4), Vol. XXVII (1909); Ferguson and Merwin, *Amer. Jour. Sci.* (4), Vol. XXXVIII, August, 1919.

in conjunction with the diagram, it will be observed that it experiences a sharp change in direction at the point indicating diopside.

Now in the hyalophane series, we possess sufficient data to show that the specific-gravity curve is straight and therefore that there is no "molecular compound" between orthoclase and celsian. Consequently we must reject the theory stated by Miers, Moses, and Parsons as untenable.

THREE-COMPONENT SYSTEMS

TERNARY DIAGRAMS

In dealing with two-component systems we have to consider two variables—the temperature and the composition. This necessitates the employment of two-dimensional diagrams. But with three components we must employ three dimensions, in other words, solid figures. These are bulky affairs which are difficult to represent upon paper. There are two methods by means of which this may be accomplished: first, by perspective drawings (special form of "block diagram"); or second, by plan drawings, ignoring the vertical co-ordinate (temperature), and projecting the liquidus surface to the base. The base is an equilateral triangle. The lines forming its side are the plan views of the binary systems. The corners, then, represent the pure components. This method, developed by Roozeboom, divides the sides of the equilateral triangle into 100 parts. The percentage composition of each of the three components, forming the ternary system, is obtained from its position and the distance of the point P (see Fig. 9) from the three sides of the triangle in directions parallel to the sides.

The procedure of representing a three-component mixture or solution by a point within the triangle can best be shown by an illustration. Let us suppose we wish to represent a mixture composed of 50 per cent of L, 30 per cent of M, and 20 per cent of N. First 50 units are measured off on the side of the triangle LM (Fig. 9) from the corner M. Let this be point A. Next the constructional line AB is drawn parallel with the line MN, as shown. From L, 30 units are measured off on the side ML. This is point C. From C the line CD is drawn parallel to LN.

AB and *CD* intersect at point *P*. Through *P* the line *EF* is drawn parallel to the remaining side, *ML*. The point *P* represents the composition of this ternary system. By consulting the figures at the side of the triangle the method of representation is made clear.

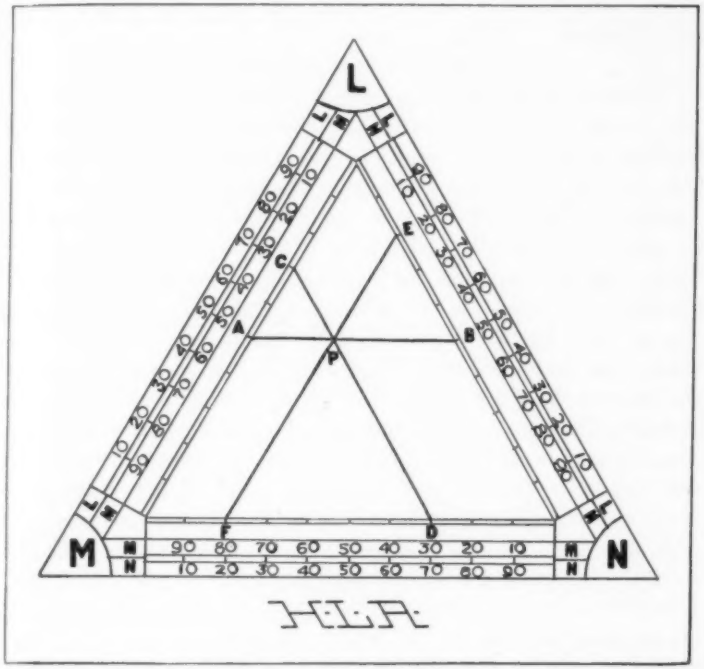

FIG. 9.—Ternary diagram, illustrating the method of indicating by a point (P) the composition of a specimen consisting of 50 per cent of *L*, 30 per cent of *M*, and 20 per cent of *N*.

By means of such triangular diagrams we can represent in a most direct manner the thermo-equilibrium diagram of a three-component system. If we employ a sufficient number of these figures we could discuss the complete feldspar system with the aid of the phase rule. The following are the ternary systems that would be necessary to that end: (1) potash-soda-lime, (2) potash-soda-barium, (3) potash-soda-carnegieite, (4) soda-lime-barium,

(5) soda-lime-carnegieite, (6) soda-barium-carnegieite, (7) lime-barium-carnegieite, (8) potash-barium-carnegieite, (9) potash-barium-lime, and (10) potash-lime-carnegieite.

As it is not possible, within the limits of the present paper, to discuss all of these ternary systems, we are compelled to confine our considerations to the most important series, the potash-soda-lime feldspars.

THE POTASH-SODA-LIME FELDSPARS

The first important paper outlining the ternary system, K-, Na-, Ca-feldspars, appeared in 1905 from the pen of J. H. L. Vogt.[1] Tracings of his original figures are here reproduced in Figure 10. The two upper diagrams illustrate the conventional method of representing the space model. The plagioclase series will be recognized as occupying the back plane. It will be seen that Vogt's conception of the *solidus* $T_{An}dT_{Ab}$ was that it assumed a straight line, which recent laboratory work has modified to a concave one as will be recalled by consulting Figure 2. The binary solubility lines extending from the eutectic temperatures to the base of the space model, which indicate low or normal temperatures, are not drawn. In the plan view the ternary solubility lines, *hg* and *ki*, at eutectic temperature, are shown projected to the base. The plan view may represent the ternary diagram at eutectic temperatures, or the diagram at normal temperatures provided the binary solubility lines are vertical. Vogt's original conception was that these lines were vertical. However, Warren has correctly suggested that these lines should be inclined, approaching the sides of the binary diagram with lowering temperature. This modification is called for in order to explain the formation of perthites ("perthoids") due to exsolution.

The Or-An binary is more or less hypothetical.

If the plan view be considered as a transverse section of the diagram cut at eutectic temperature, the areas *AnAbgh* and *kiOr* represent solid solutions of the components at this temperature. At normal temperature these areas should be more restricted than is actually shown by Vogt, occupying less space on the diagram. Positions outside of these areas represent compositions where

[1] J. H. L. Vogt, *Tschermak's Mineralog. und Petrogr. Mitt.* (1905), pp. 24 *et seq.*

Science & Industry
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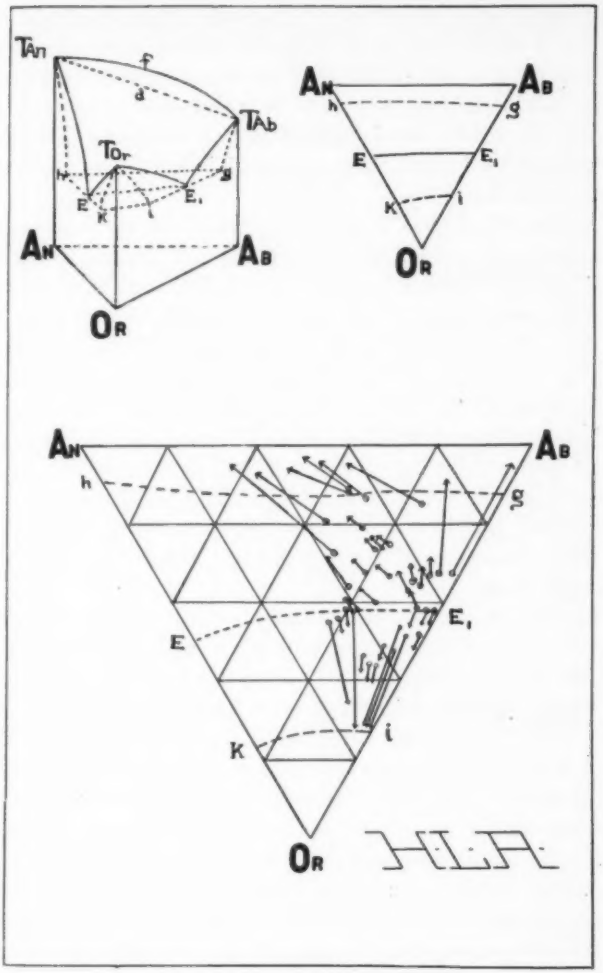


FIG. 10.—The ternary diagram of the potash-soda-lime feldspar, after Vogt. The first diagram is the perspective method of representing the solid model. The one to the right is the projection of the same to the base. The lower diagram shows the change in composition during crystallization. The circles represent the composition of the first-formed feldspars, the arrows show the direction of the change in composition taken by the subsequent forming minerals, and the arrow heads themselves indicate the composition of the last-formed minerals.

two-phase systems coexist in equilibrium. Because of the great viscosity of the high alkali feldspars we can expect that solid solutions can exist as metastable systems in the regions between the ternary solubility lines, but with increased lime content, regions near An, the ability of these feldspars to undercool and remain homogeneous at normal temperatures decreases to a point where intergrowths are rare.

The line EE_1 joins the eutectic points of the two eutectiferous binaries; and is consequently called the eutectic line. Although Vogt in the perspective drawing shows the eutectic line EE_1 horizontal, the probability is that E is situated at a higher temperature than E_1. We do not know the actual temperatures of the binary eutectics, but there is some evidence to suspect that the main portion of the solidus surface slopes down from E to E_1.

Figure 11 shows the liquidus and the solidus surfaces of the ternary system projected to the base and represented by contours of equal temperatures: isotherms. These diagrams are only approximate, but in spite of that fact it must be remembered that they constitute the rather meager basis upon which our knowledge rests.

Vogt pointed out that the feldspars which first crystallize from a magma are of different composition from those that form during the later stages of freezing. The early formed crystals are of the orthoclastic or microclinic type if the ratio of the potash component to the soda member plus anorthite was greater than the eutectic ratio. If the ratio, on the other hand, was less than that of the eutectic then the feldspars formed during the later stages of crystallization would be plagioclase. These phenomena have been indicated in Vogt's diagram in the lower part of Figure 10. The little circles represent the composition of the first-formed feldspars, and the arrows show the direction of the change in composition taken by the subsequent forming minerals, the arrow heads themselves indicating the composition of the last-formed minerals. The diagram clearly shows that during the freezing of a melt of eutectic composition the feldspars separate from that ratio toward both the potash and plagioclase areas. In other words the feldspars "split along the eutectic line." The consequences that

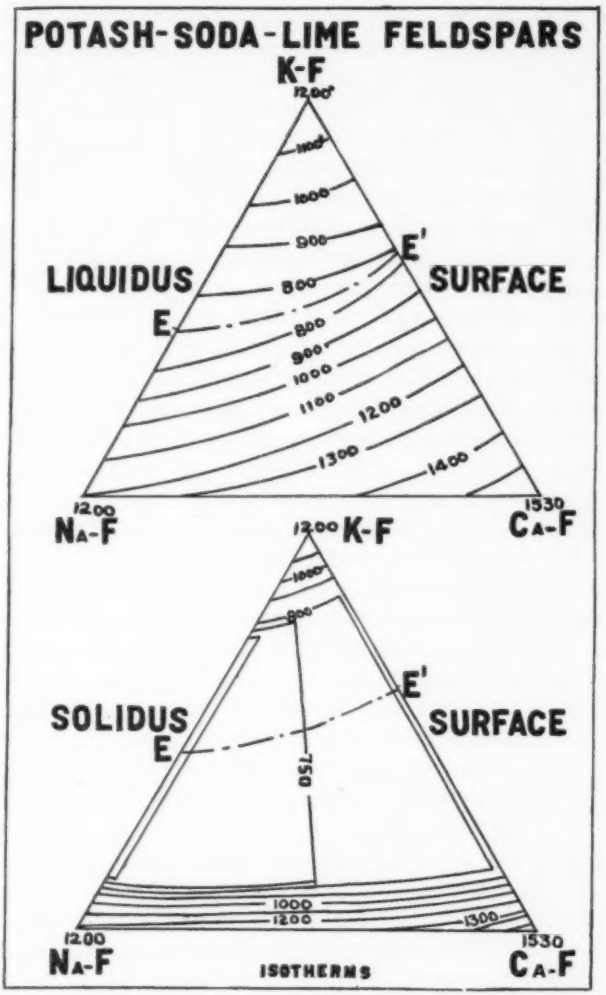


FIG. 11.—The liquidus and solidus surfaces of the ternary system, potash-soda-lime feldspars, projected to the base and represented by contours of equal temperatures or isotherms.

follow from this phenomenon are that, in the simple freezing of a magma, the maximum number of stable feldspathic phases is two, and these possess fairly constant compositions. The feldspathic content of igneous rocks, therefore, is comparatively simple in contrast with its complexity generally found in sedimentary rocks. This fact constitutes a useful criterion in distinguishing orthogneisses from paragneisses.

The complete thermo-equilibrium space model of these feldspars should show the dimorphism of the potash and the soda components. The discussion of this phase of the subject has shown that we do not possess sufficient data to supply the lines, the surfaces, and the spaces within the model to make it complete. The lack of this information seriously handicaps the interpretative petrologist. It is hoped, in spite of the obvious difficulties, that laboratory experimental work may supply the missing information.

Physical Properties of the Potash-Soda-Lime Feldspars.—In dealing with a two-component system the change in the physical properties and their relations to the change in composition is best indicated by lines upon a plane surface. In the case of three components, as here under consideration, these variables are represented by surfaces. The most convenient method of indicating to the eye the nature of these surfaces is by the use of contours. On these the *liquidus* and the *solidus* surfaces may be shown by lines of equal temperature or isotherms, the value of the extinction angles by isogonic lines, and the values of the specific gravity by lines indicating equal density, etc. All of these contoured surfaces are drawn upon triangular bases showing the interrelationships of these properties to the composition itself. To be able to show with accuracy properties of the potash-soda-lime feldspars by means of these surfaces is an ideal not yet fully realized. If the reader will bear in mind that the following diagrams are conjectural because of our total lack of definite information about the potash-lime feldspars and to be studied as the stratigrapher studies and interprets his paleogeographic maps then there will be no misunderstanding in regard to them. The writer feels that there is great value in the construction of these tentative diagrams, for

they demonstrate, as no other method can, the nature of these minerals and the constants by means of which they are identified.

Extinction Angles: Inasmuch as the extinction angles of the plagioclase and the potash-soda series constitute the most serviceable means of identification, it is important that some attempt be made to draw the isogonic lines of the orthoclase-albite-anorthite and the microcline-albite-anorthite systems for the two faces (010) and (001). This involves the use of four triangular diagrams, which are reproduced as diagrams 1 to 4 in Figure 12. When the extinction angle of natural specimen has been measured an inspection of the proper diagram shows that considerable compositional range is indicated by its curve. The extinction angle, therefore, does not appear to constitute a conclusive identification of composition. The common procedure is to ignore the least-abundant component and thus attempt to reduce the system to a simple binary. The writer is convinced, however, that this sacrifices considerable accuracy. It is much more accurate to assume the presence of a small amount of the third component rather than to ignore it altogether. As a result of examining nearly 1,300 analyses of feldspars the following empirical rule is offered: Albites contain an average of 6 per cent of the potash component; oligoclases, 8 per cent; andesines, 7 per cent; labradorites, 6 per cent; bytownites, 4 per cent; and anorthites, 3 per cent. Even though these figures are not constant (see "potash oligoclase" for example) yet the writer is convinced that if these are assumed the petrologist will be nearer to the truth than if the third component is ignored. A similar set of figures might be set up for the potash-soda side of the triangle. In soda orthoclase and soda microcline the percentage of the lime component is 2 or 3 per cent. In potash albite and anorthoclases of hyperperthitic composition the percentage of the lime component is greater, reaching in some instances as high a value as 15 or 18 per cent. This is suggested in diagram 5 in Figure 12 by the irregular line within the triangle. It represents the approximate average composition of 954 natural feldspars actually recast and plotted.

The point of intersection of this compositional line and of the measured extinction angle line represents the true composition of

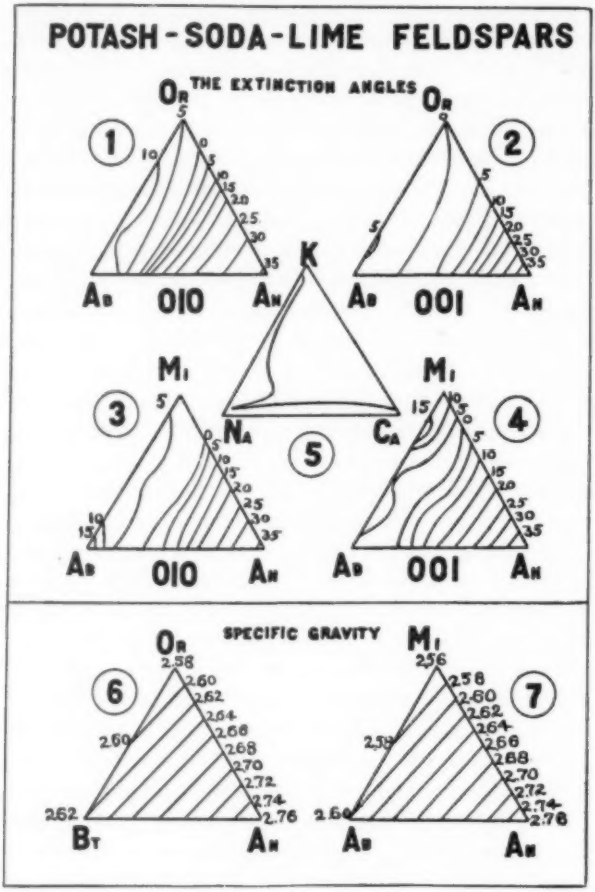


FIG. 12.—The diagrams, 1 to 4, are attempts to show the extinction angles of the potash-soda-lime feldspars by means of isogenic lines. Diagram 5 shows the approximate average composition of natural feldspars. The intersection of this compositional line and the proper isogenic lines determines the composition of the specimen under examination. Diagrams 6 and 7 show the specific gravities of the orthoclase-barbierite-anorthite and the microcline-albite-anorthite systems. All of these diagrams are tentative.

Science & Industry
Department

the specimen more accurately than the intersection of the isogonic line and the side of the triangle. The latter procedure is the one commonly followed although the petrologist does not express the method in these terms.

An important fact, which needs to be emphasized, is that in using the conventional extinction curves of the textbooks to determine the percentage of the soda component in a plagioclase, it is not possible to determine the percentage of the lime and potash members with anywhere near the same accuracy. The reason for this fact is that the isogonic lines are nearly parallel to the potash-soda side of the triangle. It follows then that the most satisfactory means of determining the true composition, the percentage of each of the three components, is to consider that the value of the extinction angles gives the percentage of the soda component only. Knowing this fact it can be ascertained what particular subdivision of the series is being examined. By consulting the compositional line or by reference to the average percentage of the potash component in the natural plagioclase, the approximate amount of the third component is found. The amount of the line component is the remainder. This can be illustrated: Suppose the extinction angles of a specimen were found to be 23° on the (010) face and 10° on the (001) face. The theoretical composition of this specimen would be found from the plot shown in Figure 3 to be $Ab_{40}An_{60}$, but by the method here suggested the value of the Ab alone is correct. Now it has been found that most labradorites contain an average of 6 per cent of the potash component. Thus the amount of the lime member is 60 minus 6, or 54 per cent. Therefore the composition of the specimen is K-feldspar, 6; Na-feldspar, 40; Ca-feldspar, 54.

The fact that the isogonic lines are nearly parallel to the potash-soda side of the triangle is the reason why it is easier to determine the composition of the plagioclase feldspars than that of the potash-soda series; for the isogonic lines intersect that side of the diagram more frequently. To state it in another way, there is a greater change in the value of the extinction angles per unit change in composition. As most petrographic determinations of extinction angles are only approximate it follows that an error in

the extinction angles of the plagioclase feldspars does not involve such a large error in the determination of the composition as it does in the case of the potash-soda feldspars. This is, perhaps, the reason that petrographers have thought it was impossible to determine, microscopically, the chemical composition of the latter series.

Specific Gravities: We have seen that the specific-gravity curves for the potash-soda series probably are represented by two non-parallel lines; the upper lines representing the density of the monoclinic modifications and the lower those of the triclinic forms. The specific gravities of the plagioclase feldspars, Ab-An, can properly be represented by a straight line inclined upward from albite to anorthite. Taking the curves for these binary systems it has been possible to construct the diagrams 6 and 7 in Figure 12 for the ternary system. They are instructive, even though they lack confirmation on the potash-lime side. They also illustrate the difficulty in the determination of the potash-soda series in that only a few lines intersect the potash-soda binary side, while a greater number cut the plagioclase side.

The diagrams indicate an inclined flat surface of the space model which they represent. One diagram is for the orthoclase-barbierite-anorthite system; the other, the microcline-albite-anorthite feldspars. Two others might be drawn: orthoclase-albite-anorthite and microcline-barbierite-anorthite.

CLASSIFICATION

It is important that we attempt to sum up the ternary system, potash-soda-lime feldspars, by offering a reasonable classification of the same. To accomplish this the writer has had to venture upon untrodden ground and therefore realizes his limitations. To overcome some of the objections that may be raised against it on the ground that it is too comprehensive or too complicated, the scheme is offered in two forms: one which may be called the technical classification and the other the popular one. They are shown in Figure 13.

In proposing these classifications absolutely new names have been avoided so far as possible. For the row of areas beginning with potash oligoclase and ending with potash bytownite the

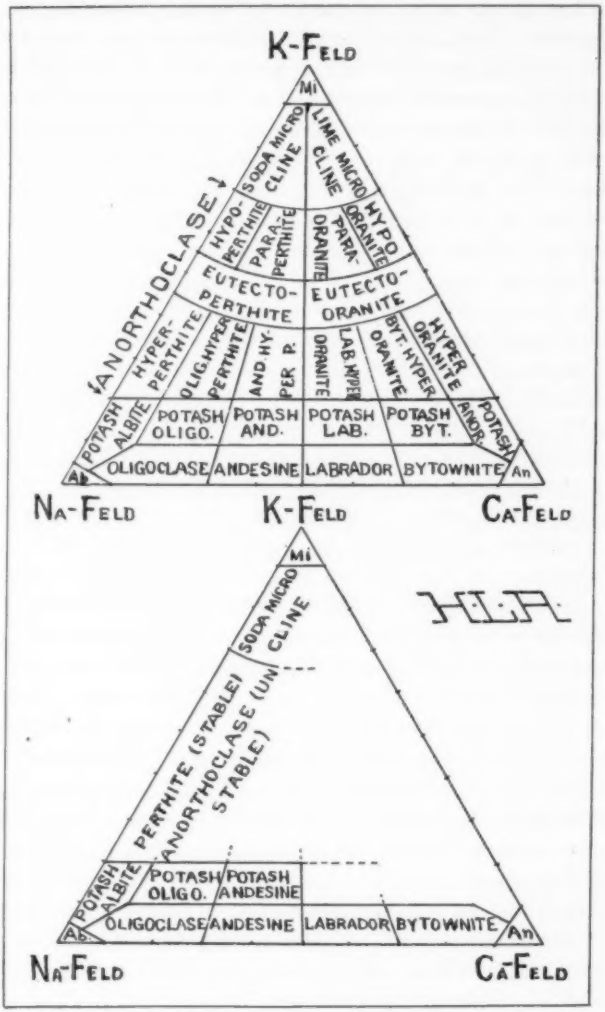


FIG. 13.—Proposed schemes for classification of the potash-soda-lime feldspars. The upper diagram is the "technical" while the lower one is the "popular" scheme. Orthoclasic feldspars are not indicated; the microclinic forms being shown instead.

writer has merely extended the term "potash" as given to the feldspar from Tyveholmen, Norway, to other plagioclasic feldspars with a potash-component content greater than 10 per cent. The prefixes hypo-, eutecto-, and hyper- have been pointed out before as adaptations of metallographic nomenclature. The term "oranite" is employed for feldspars of the potash-lime ranges analogous to perthite. The derivation of the term is indicated by the first two letters of *or*thoclase and *an*orthite with the mineralogical ending *-ite*. Thus with these prefixes and the term "oranite" many areas can be supplied with suitable names. In the triangles between hypoperthite and hypo-oranite the proposed terms "para-perthite" and "para-oranite" are not very satisfactory. The Greek παρα- possesses a wide range of meanings, one of which implies "a position alongside of" and "beside of," which is the meaning desired here. Criticism of the term, however, may be made on the ground that the geologist and the mineralogist use paragneiss, paraschist, paragenesis, paramorphism, paramorph, etc., without attaching this significance to the prefix. It is a term which can be temporarily used until a better one is found.

EXAMINATION OF CHEMICAL ANALYSES OF FELDSPARS

It is very desirable to know what is the actual composition of natural specimens of feldspars, and how these have been classified. Consequently many chemical analyses have been examined. About 1,300 analyses of feldspars from all parts of the world were collected from the literature. Of this number 954 were considered to be suitable for recasting and plotting. In dealing with such a large number of analyses it was obviously impossible to recast each by first obtaining the molecular ratio of each oxide and combining them in the usual manner. Therefore short cuts to approximately the same results were used. It was first assumed that each specimen was composed of only three components, the potash, soda, and lime feldspars, excepting in case where BaO was determined, indicating the presence of celsian.

The percentage of each component was determined directly from the percentage of the characteristic base. Thus all of the K_2O was assumed to be in $KAlSi_3O_8$; all the Na_2O in $NaAlSi_3O_8$, and

the CaO in $CaAl_2Si_2O_8$. The small amounts of extraneous bases and water, such as Fe_2O_3, FeO, MgO, H_2O, etc., that are very frequently present in natural specimens, have been ignored. The following factors were used in calculating the percentage of each of the three components:

Component	Formula	Oxide	Factor
Potash.....	$KAlSi_3O_8$	K_2O	16.85
Sodium.....	$NaAlSi_3O_8$	Na_2O	11.83
Lime.....	$CaAl_2Si_2O_8$	CaO	20.21

The sum of these three components should be 100 per cent theoretically but as a matter of fact it rarely was. The majority of these totals was about 96 per cent, indicating if the analyses were accurately made, that the specimens were only 96 per cent pure feldspar. The inferior quality of many of the analyses or the probable presence of additional components in the system were emphasized when the sum of the feldspar components was considerably above or below 100. All those showing a total below 85 and above 110 have been rejected. The three feldspar components were then proportionately raised or lowered to 100 per cent. All the calculations were performed on a 20-inch slide rule; the errors resulting from its use being within the limits of the chemical analyses and within plotting range upon the triangular co-ordinate base used (Fig. 19).

It is known that not all of the Na_2O is necessarily in $NaAlSi_3O_8$ in every case. This base may be present in the form of nephelite or carnegieite in addition to the albite. Foot and Bradley[1] have pointed out such a possibility and say: "Albite sometimes occurs, associated with an excess of the constituents . . . . either in free condition, as corundum or silica, or in combination as nephelite." When the sum of the three feldspar components, calculated from a reliable chemical analysis, exceeds 100 per cent then the number of components is probably in excess of the three assumed. This condition is far more common than is usually supposed. Washington

[1] Foot and Bradley, "On Solid Solutions in Minerals, III," "The Constant Composition of Albite," *Amer. Jour. Sci.* (4), XXXVI, 47.

and Wright[1] have shown that the plagioclase from Limosa contains an appreciable amount of carnegieite in solid solution.

The chemical analysis is as follows:

SiO_2	52.77	CaO	10.66
Al_2O_3	29.50	Na_2O	5.40
Fe_2O_3	.65	K_2O	.74
FeO	.17	H_2O	.36
MgO	.05	Total	100.30

They recast the analyses in terms of four components:

Potash component	$KAlSi_3O_8$	4.48
Sodium component	$NaAlSi_3O_8$	36.16
Lime component	$CaAl_2Si_2O_8$	53.78
Carnegieite	$Na_2Al_2Si_2O_8$	5.58

If, however, the presence of the carnegieite in the feldspar was not suspected and the analysis recast on the basis of only the three components then the result would be as follows:

Potash component	4.48
Sodium component	54.20
Lime component	53.78

with the excessive total of 112.46 per cent. A short method of obtaining the proper composition of a carnegieite bearing feldspar can be secured by setting up the ratio, Na-component without carnegieite: 1 = Na-component with carnegieite: .6667.

Because of the probability that many of the analyses here recast and plotted, even though tested by the method above mentioned, are inferior to those now being made in many laboratories, there are limitations to the conclusions that can be safely drawn from their study and comparison. Yet it is believed that they illustrate beyond much doubt that the term "orthoclase" is used in a very loose manner, quite inconsistent with present-day standards. Fair maximum and minimum limits for the range assumed by natural "orthoclase" specimens among the analyses examined were:

	K-feldspar	Na-feldspar	Ca-feldspar
from	87.60	11.05	1.35
to	49.20	48.60	2.20

[1] H. S. Washington and F. E. Wright, "A Feldspar from Limosa and the Existence of a Soda-Anorthite (Carnegieite)," *Amer. Jour. Sci.* (4), XXIX (1910), 52–70.

Science & Industry
Department

Furthermore in only a very few cases where the three oxides, Na_2O, K_2O, and especially CaO, had been looked for, was any one of the three components entirely wanting. Such a revelation may not be surprising to the petrographer for he knows that it is usually impossible to determine with a microscope the composition of the alkali feldspars with anything like the accuracy obtainable in case of the plagioclase series.

The writer has secured some sixty specimens of so-called orthoclase from many world-famous localities and has satisfied himself after careful petrographic examination of them in thin sections and in crushed fragments that in the majority of cases the mineral is not orthoclase at all, but that it is a microcline relatively high in soda and more frequently a microclinic perthite. It is but a reasonable assumption, therefore, that the specimens which furnished the material from which the analyses have been made had not been examined petrographically, for if such examinations had been made, the name orthoclase would not have been applied to them in such a careless manner. The names given in Figure 19 are the original ones published in connection with the chemical analyses which, as already stated, have been secured from many sources. The works on mineralogy by Dana, Hintze, Bayley, etc., have contributed many. Various bulletins of the state and federal geological surveys have been consulted. The volume of the Asches on *The Silicates in Chemistry and Commerce* has furnished a considerable number of analyses of the plagioclase series. The analyses themselves are not here reproduced but the references to the literature are given in the bibliography.

Hintze does not distinguish the analyses of orthoclase from those of microcline, grouping them together. This necessitates the symbol for "orthoclase and microcline." The purpose of this triangle diagram did not warrant an extreme degree of accuracy and consequently the circles have been located as close to the actual recast figures as possible without any overlapping, which would cause undue confusion in recognizing the different species there represented.

In many ways the diagram (Fig. 19) speaks for itself. It clearly indicates that most if not nearly all feldspar specimens are three-component systems.

MICROSCOPIC EXAMINATION OF NATURAL FELDSPARS

The present section contains the results of microscopic and chemical analyses of typical feldspars from many parts of the world.

The optical properties of the feldspars were only determined to the extent necessary for an identification of the species. The extinction angles on (010) and (001) were determined by Michel-Levy's "statistical" method[1] on crushed fragments, which were properly sized by passing through sieves of 100 mesh, caught on screens of 120 mesh, and then placed in a suitable mounting fluid —such as clove oil. A large share of the determinations were made with monochromatic (sodium) light and the stage of the petrographic microscope rotated from each position to extinction. The recorded results are the averages of five readings. The orientation of the fragments was ascertained in the following manner. The faces were recognized by the cleavage, the interference figure, and the twinning. The fragments broken into plates parallel to the base (001) were found to be more common than those parallel to (010); the former were often identified by traces of the albite twinning. The (010) faces are more likely to have parallel edges due to the cleavage.

For this experimental work the writer naturally chose specimens of feldspars whose chemical composition was known, and whose chemical analyses were later recast into percentages of the three feldspar components. Upon this basis the interrelationship of the optical properties and the composition were ascertained which enabled the writer to draw the diagrams of the extinction angles of the system. The reader must remember that the close check between the chemical analyses and that inferred from the optical characters is the result of using the chemical analyses for the purpose of establishing the relations between chemical composition and physical properties, and so lead to methods of identification.

The percentage of the feldspar phases, when more than one was present in the specimens, was determined by a method analogous

[1] Michel-Levy, "De l'emploi du microscope polarisant a lumière parallele pour l'étude des plaques minces les roches eruptives," *Ann. des Mines* (December, 1877), pp. 392, 471.

to that developed by Rosiwal. The outlines of the different phases in a given field of the thin section were traced upon paper with the aid of a camera lucida. The areas of these grains were measured by a polar planimeter. The sum of the areas occupied by the grains of the different minerals was assumed to be proportional to their volumes. By multiplying the volumes by the specific gravities of the minerals the proportion by weight was secured and then calculated to 100 per cent. Usually four different microscopic fields in each slide were analyzed and their results averaged. Care was taken to use an optical system (objectives and oculars) which would give the largest practical field. The composition of each phase was determined by the extinction angles of crushed fragments. The first portion of each table shows the percentage of each of the phases present and their composition. The composition of each phase is given in percentages of each of the three feldspar components, totaling 100 per cent. In the second portion of the tables the percentage of each component is calculated upon a basis of 100 per cent for the entire specimen. The sum of the different components thus obtained gives the composition of the entire specimen after the manner of a recast chemical analysis. Consequently a chemical analysis, recast, would have to be rearranged by distributing the components into the various phases present in order to appreciate the true nature of the specimen. This indicates that the perthitic feldspars are much more complicated than is generally thought. The accuracy of the proper distribution of the components into the phases is directly dependent upon the accuracy of the thermo-equilibrium diagram and the degree of undercooling of the feldspar system under consideration. Until the diagrams of these minerals can be put upon a quantitative basis our examinations will be approximate only.

EXAMPLES OF PLAGIOCLASE FELDSPARS

1. *"Albite," Amelia Court House, Virginia.* (*Specimen 961.*)

Microscopic examination, thin section: Broad albite twinning.
Extinction angles, crushed fragments:

(010) 18.3°
(001) 3.0°

Inferred composition:

K-feldspar..... 1.0
Na-feldspar..... 97.0
Ca-feldspar..... 2.0

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	H_2O	Fe_2O_3	Total
1.....	67.06	21.72	1.59	.03	10.01	.39	.....	.....	100.80
2.....	68.44	19.35	.....	.....	11.67	.43	.....	.....	99.89
3.....	68.22	19.06	.40	.....	11.47	.20	.69	.15	100.19

	K-feldspar	Na-feldspar	Ca-feldspar
1.....	2.24	90.60	7.14
2.....	2.49	97.51	.....
3.....	1.2	96.9	1.9
Microscopic	1.0	97.0	2.0

Classification: Albite.

Analyses 1 and 2. Foote and Bradley, *Amer. Jour. Sci.* (4), XXXVI (1913), 47, after Robertson and Musgrave. *Chem. News*, XLVI (1882), 204. Dana, *System of Mineralogy*. Albite 15.

Analysis 3. Allen and Day, *Carnegie Inst. Pub. 31*, p. 48, G. P. Merrill.

2. *"Oligoclase," Arendal, Norway.* (*Specimen 960.*)

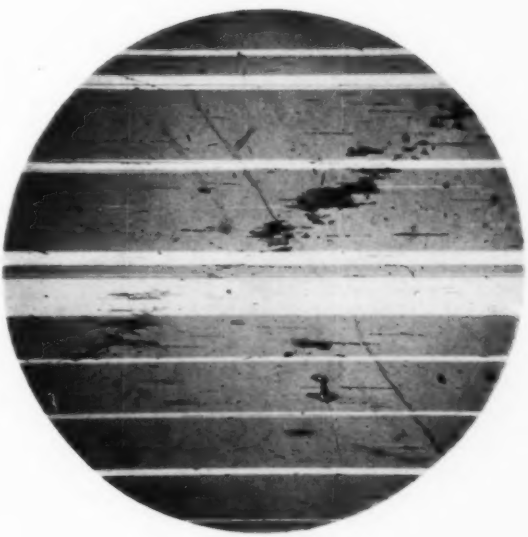
Microscopic examination, thin section: Perfectly normal plagioclase with albite twinning.
Extinction angles, crushed fragments:

(010) 4.0°
(001) 1.0°

Index of refraction, beta: 1.547
Inferred composition, ignoring potash component $Ab_{75}An_{25}$.
Inferred composition, considering potash component:

K-feldspar..... 10.0
Na-feldspar..... 75.0
Ca-feldspar..... 15.0

A



B

A. Albite, Amelia Court House, Virginia. Polarized light. ×30. Specimen 961.

B. Labradorite, near Nain, Labrador. Polarized light. ×30. Specimen 967.

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	H_2O	Total
1.....	63.53	24.05	2.60	1.86	8.02	.....	.90	100.00
2.....	63.51	23.09	2.44	2.19	9.37	.77	.....	101.37

	K-feldspar	Na-feldspar	Ca-feldspar
1.....	11.8	74.5	13.7
2.....	12.3	76.0	11.7
Microscopic.....	10.0	75.0	15.0

Classification: Oligoclase.

Analysis 1. Asch, *The Silicates in Chemistry and Commerce.* Analyses 9 and 34, which are duplicated. Asch 9, Des Cloizeaux, *Bull. Soc. Min.* 7 (1884), 225. Asch 34, Rosales, *Pogg. Ann.* (1842), 55, 109. Analyzed by Dirvell.

Analysis 2. Asch, *ibid.*, Analysis 71, Hagen, *Pogg. Ann.* 44 (1838), 329. Analyzed by Hagen. See Dana, *System of Mineralogy.* Extinctions on:

ARENDAL

CaO Percentage	001	010
2.50	0–2	10–12.5
2.60	0–1.5	9–12
2.81	0–2	10–12
4.20	.5–1	2–4

3. "Oligoclase, Sunstone," Tvedestrand, Norway. (Specimen 970.)

Microscopic examination, thin section: Oligoclase with inclusions of hematite, which are in all probability due to exsolution.[1]

Extinction angles, crushed fragments:

	Mallard*	Schuster†	Andersen‡	Dana§	Alling
(010).....	2°–5°	3°34′	3.5°	2°–4°	2.5°
(001).....	1°–1°27′	1°10′	1°	1°30′	1.0°

* E. Mallard, *Bull. Soc. Min. France,* IV (1880), 104.
† Max Schuster, *Tschernaks Min. und Petrog. Mitt.,* III (1880), 164.
‡ Olaf Andersen, *Amer. Jour. Sci.* (4), XXX (1915), 379–80.
§ James D. Dana, *System of Mineralogy,* sixth ed., p. 336.

Inferred composition from the writer's measurements, ignoring the potash component: $Ab_{70}An_{30}$.

Inferred composition, considering potash component:

K-feldspar..... 7.0
Na-feldspar..... 70.0
Ca-feldspar.....23.0

[1] Olaf Andersen, *Amer. Jour. Sci.* (4), XXX (1915), 379.

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	Total
Analysis	61.30	23.77	0.36	4.78	1.29	8.50	100.00

	K-feldspar	Na-feldspar	Ca-feldspar
Chemical	7.45	69.62	22.93
Microscopic	7.0	70.0	23.0

Classification: Oligoclase.

Analysis. James D. Dana, *System of Mineralogy.* Oligoclase and oligoclase-albite No. 11. Asch, *The Silicates in Chemistry and Commerce.* No. 40. Scheerer, *Poggendorff's Annalen,* 64, 1845, 153.

4. "Labradorite," near Nain, Labrador. (Specimen 967.)

Microscopic examination, thin section: Normal plagioclase with albite twinning. Small inclusions of rutile, ilmenite (?), diopside, and hematite. Extinction angles, crushed fragments:

(010)	20°
(001)	12°
Maximum, Zone ⊥ (010)	33°

Inferred composition, ignoring potash component: $Ab_{44}An_{56}$.
Inferred composition, considering potash component:

K-feldspar	2.0
Na-feldspar	44.0
Ca-feldspar	54.0

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	Ign	Fe_2O_3	MgO	Total
1	56.00	27.50	10.10	5.00	.40	.....	.70	.10	99.80
2	56.18	27.33	10.33	5.17	.36	.....	1.38	.....	100.75
3	54.75	27.76	10.60	5.13	.53	.56	.69	.....	100.02

	K-feldspar	Na-feldspar	Ca-feldspar
1	2.50	44.70	52.41
2	2.21	45.10	52.61
3	3.18	43.80	53.01
Microscopic	2.0	44.0	54.0

Classification: Labradorite.

Analyses. James D. Dana, *System of Mineralogy, Labradorite Nos. 23, 24, 25.*

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EXAMPLES OF POTASH-SODA FELDSPARS

1. *"Orthoclase," "Adularia coated with chlorite," Scopi, Switzerland. (Specimen 988.)*

Microscopic examination, thin section: Clear, untwinned potassic feldspar.
Extinction angles, crushed fragments:

(010)	5.0°
(001)	0.4°

Inferred composition, considering potash component:

K-feldspar	92.0
Na-feldspar	6.0
Ca-feldspar	2.0

This is one of the very few specimens examined to which the term "orthoclase" can be assigned in accordance with the nomenclature here adopted.
Classification: True orthoclase.

2. *"Chesterlite," Poor House Quarry, West Chester, Pa. (Specimen 997.)*

Microscopic examination, thin section: Broad phantom twinning, suggesting microcline.
Extinction angles, crushed fragments:

(010)	6.0°
(001)	16.5°

Inferred composition, considering the potash component:

K-feldspar	83.0
Na-feldspar	14.0
Ca-feldspar	3.0

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	K_2O	Na_2O	Ign	Fe_2O	CaO	MgO	Total
1	64.97	17.65	14.02	1.69	.65	.50	.50	.27	100.36
	K-feldspar		Na-feldspar				Ca-feldspar		
Chemical	82.8		14.2				3.0		
Microscopic	83.0		14.0				3.0		

Classification: Popular and technical: Soda microcline.

Analysis. James D. Dana, *System of Mineralogy.* Microcline 5. Hintze, *Handbuch der Mineralogie.* "Orthoclase and Microcline Kalifeldspath," CCXCII.

3. *"Orthoclase, var. Adularia," Eggerhorn, Switzerland.* (*Specimen 989.*)

Microscopic examination, thin section: Very coarse phantom twinning with wavy extinction. Some areas comparatively free from microclinic texture, and appear like perfect development of orthoclasic feldspar.

Extinction angles, crushed fragments:

Untwinned	(010)	7.2
Untwinned	(001)	1.4
Twinned	(010)	6.5
Twinned	(001)	17.0

Inferred composition:

K-feldspar	82.0
Na-feldspar	16.0
Ca-feldspar	2.0

The probable character of the feldspar is that it is in the process of inverting from soda orthoclase to soda microcline.

Classification: Soda orthoclase—soda microcline.

4. *"Microcline," Georgetown, Maine.* (*Specimen 995.*)

Microscopic examination, thin section: It is readily seen that the specimen is a microclinic microperthite.

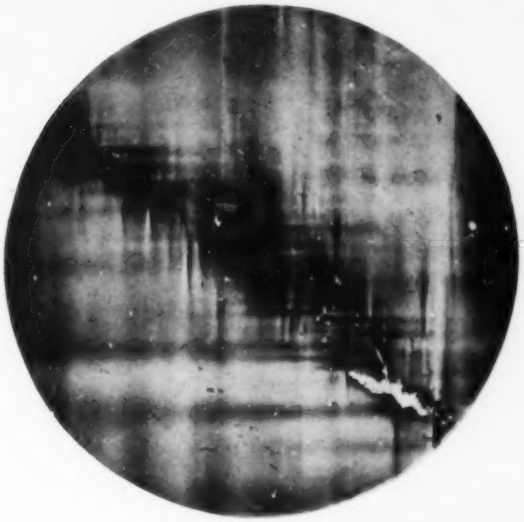
Extinction angles, crushed fragments:

Potash phase	(010)	6.0°
	(001)	15.5°
Soda phase	(010)	4.0°
	(001)	1.0°

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	88.0	15.0
Na-feldspar	5.0	75.0
Ca-feldspar	7.0	10.0

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar
Soda microcline	83.5	88.0	5.0	7.0
Oligoclase	16.5	15.0	75.0	10.0
		K-feldspar	Na-feldspar	Ca-feldspar
Soda microcline		73.5	4.2	5.8
Oligoclase		2.5	12.3	1.6
Total		76.0	16.5	7.4



A

B

A. Soda orthoclase inverting to soda microcline, called "Orthoclase, var. Adularia," Eggerhorn, Switzerland. Polarized light. ×30. Specimen 989.

B. Microcline microperthite (hypoperthite), called "Amazonstone," Amelia Court House, Virginia. Polarized light. ×30. Specimen 992.

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	Ign	Total
1	65.50	19.56	.....	1.58	.55	12.67	.....	99.84
2	65.23	20.09	.71	.....	2.00	11.60	.36	99.99

	K-feldspar	Na-feldspar	Ca-feldspar
1	85.8	5.3	8.9
2	80.2	19.8	.....
Microscopic	76.0	16.5	7.5

Classification:

Popular: Microcline microperthite

Technical: Microcline hypoperthite.

Analysis 1. Collection of A. A. Robbins, now on exhibition in the New York State Museum, Albany, New York.

Analysis 2. E. S. Bastin, *U.S. Geol. Surv. Bull. 420*, p. 24.

5. *"Microcline Amazonstone," Amelia Court House, Amelia County, Virginia. (Specimen 992.)*

Microscopic examination, thin section: Microclinic microperthite.

Some of the intergrowths of the potash and soda phases have an appearance as though they were primary, due to the freezing of the eutectic mixture.

The albite-oligoclase occurs in stringers which vary in thickness and are not continuous. The "linkage" areas between these blebs are characterized by a much finer Scotch-plaid type of twinning in the soda microcline which appears to be akin to anorthoclase. These areas then may be regarded as a supersaturated crystalline solid solution changing to microperthite by exsolution.

Extinction angles, crushed fragments:

Potash phase	(010)	6.4°
	(001)	17.1°
Soda phase	(010)	12.0°
	(001)	3.0

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	80.0	2.0
Na-feldspar	18.0	88.0
Ca-feldspar	2.0	10.0

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar
Soda microcline	91	80	18	2
Albite-oligoclase	9	2	88	10
Soda microcline		73.3	16.2	2.0
Albite-oligoclase		.1	7.7	.7
Total		73.4	23.9	2.7

Classification:

Popular: Microcline microperthite

Technical: Microcline hypoperthite.

6. *"Microcline," Etta Mine, one mile south of Keystone, South Dakota. (Specimen 965.)*

Microscopic examination, thin section: Microcline microperthite with quartz, diopside, sericite, and carbonates. The sodic phase of the intergrowths is oligoclase.

Extinction angles, crushed fragments:

Potash phase	(010)	6.0°
	(001)	17.0°
Soda phase	(010)	7.0°
	(001)	3.0°

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	80.	3.
Na-feldspar	17.	80.
Ca-feldspar	3.	17.

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar
Soda microcline	87.5	80	17	3
Oligoclase	12.5	3	80	17
Soda microcline		70.	14.9	2.6
Oligoclase		.3	10.0	2.2
Total		70.3	24.9	4.8

Classification:

Popular: Microcline microperthite.

Technical: Microcline hypoperthite.

7. *"Microcline," San Diego County, California. (Specimen 958.)*

Microscopic examination, thin section: Soda microcline, showing but faint microclinic twinning, and in a few areas, entirely clear. Slivers removed from the specimen with the gentle application of the knife blade show no twinning. The suggestion is strong that in grinding pieces for thin sections sufficient pressure was present to hasten the inversion of the soda orthoclase to soda microcline. To test this theory crushed fragments were heated in a quartz crucible over a Scimatco burner for one hour, three hours, and five hours. The percentage of the twinned specimens was measured in each case after the fragments had cooled. The results are tabulated below:

No.	Time of Heating in Hours	Number of Twinned Fragments Seen	Number of Untwinned Fragments Seen	Percentage of Twinned Fragments
1	0	28	64	19.6
2	1	53	90	36.8
3	3	56	48	54.0
4	5	81	34	65.0

Extinction angles, crushed fragments:

Twinned	(010)	6.5°
	(001)	17.0°
Untwinned	(010)	7.0°
	(001)	1.5°

These observations point to the fact that the specimen is in the act of inverting from the one modification to the other.

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar	Silica
Soda microcline	80	80	18	2	
Oligoclase	17	2	85	13	
Quartz	3				100
Soda microcline		64.0	14.4	1.5	
Oligoclase		0.3	14.5	2.2	
Quartz					3
Total		64.3	28.9	3.8	3.0

Classification:

Popular: Microcline microperthite

Technical: Microcline hypoperthite.

8. "Orthoclase," Sanidine Porphyry, Drachenfels, Siebenebirge, Rhenish Prussia. (Specimen 986.)

Microscopic examination, thin section: The slide slows phenocrysts of sanidine, usually zonally grown, the central portion of which is slightly more potassic than the margins.

Extinction angles, crushed fragments, the average of a large number.

(010)	9.3°
(001)	6.0°

Inferred composition:

K-feldspar	62
Na-feldspar	34
Ca-feldspar	4

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	CaO	K_2O	Na_2O	MgO	Ign	Total
	65.87	18.53	.95	10.32	3.92	.39	.44	99.92
	K-feldspar		Na-feldspar			Ca-feldspar		
Chemical	61.6		33.7			4.7		
Microscopic	62.0		34.0			4.0		

Classification: Anorthoclase, potentially hypoperthite.

Analysis. James D. Dana, *System of Mineralogy.* Orthoclase No. 6. (Rg. Min. Ch. 1003, 1860.)

9. "Sunstone," Delaware County, Pennsylvania. (Specimen F3-974.)

Microscopic examination, thin section: The slide reveals that the specimen is microclinic perthite of two periods of development. The microcline intergrown with the albitic feldspar of the first generation is holding blebs of soda-rich feldspar that are clearly the result of a later development. It is believed that the albite phase of the second generation and the small flakes of hematite are due to the decrease in solubility of these constituents of the solid phase—they are due to exsolution.

Extinction angles, crushed fragments:

Potash phase	(010)	6.5°
	(001)	17.0°
Soda phase	(010)	21.2°
	(001)	4.0°

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	80	2
Na-feldspar	17	97
Ca-feldspar	3	1

Science & Industry Department

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Phase	Percentage	Percentage	Phase	K-feld.	Na-feld.	Ca-feld.	Fe_2O_3
Perthite	K-feld.	80	93.5	Soda micro.	80	17	3	.....
	Na-feld.	19.5	6.5	Albite 2	2	97	1	.....
			19.5	Albite 1	2	97	1	.....
Hematite	.....	.5	.....	.....	.....	.....	.....	100
Perthite	Ka-feld.	80		Soda micro.	59.8	12.7	2.2	.....
	Na-feld.	19.5		Albite 2	.1	5.1	.1	.....
				Albite 1	.4	18.9	.2	.....
Hematite	.....	.5		.....	.....	.....	.....	.5
Totals	.....	.....		.....	60.3	36.7	2.5	.5

Classification:

Popular: Microcline microperthite

Technical: Microcline hypoperthite.

10. *"Microcline," Verona, Ontario, Canada. (Specimen 959.)*

Microscopic examination. The microscope shows that the specimen is really a microcline microperthite with some accessory quartz.

Extinction angles, crushed fragments:

Potash phase	(010)	6.0°
	(001)	17.9°
Soda phase	(010)	5.5°
	(001)	1.5°

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	73	2
Na-feldspar	25	80
Ca-feldspar	2	18

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar
Soda microcline	81	73	25	2
Oligoclase	19	2	80	18
Soda microcline	.....	59.4	20.1	1.6
Oligoclase	.....	.4	15.2	3.4
Total	100.0	59.4	35.3	5.0

Classification:

Popular: Microcline microperthite.

Technical: Microcline hypoperthite.

11. "Microcline-Amazonstone," Mineral Hill, Pennsylvania. (Specimen 964.)

Microscopic examination, thin section: Under the microscope it is readily seen that there are two generations of perthitic intergrowths. The potash phase, which is intergrown with a soda-rich feldspar, is in turn full of secondary blebs of a soda phase. This may be explained as due to the fact that complete separation of the two phases was accomplished at relatively high temperatures, while the subsequent separation has taken place at more moderate temperatures. The latter phenomenon is probably due to decreased solubility as determined by the slope of the solubility-saturation curve, line *AL* in Figure 4. The fact that the "secondary" blebs of potash feldspar in the original member, rich in soda, are not seen, even under high magnifications (950 diameters), testifies to the nearly vertical character of the corresponding curve, *BM* in Figure 4.

Extinction angles, crushed fragments:

Potash phase	(010)	7.2°
	(001)	16.9°
Soda phase	(010)	19.0°
	(001)	4.8°

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Phase	Percentage	Percentage	Phase	K-feldspar	Na-feldspar	Ca-feldspar	SiO_2
Perthite	K-feld.	80	90	Soda micro.	80.0	17.0	3.0	.....
	Na-feld		10	Albite 2	3.0	95.0	2.0	
		19.6	19.6	Albite 1	3.0	95.0	2.0	
Quartz	Quartz	.4	.....	.....	.....	.....	.....	100
Perthite	K-feld.	80		Soda micro.	57.6	12.2	2.2	.....
				Albite 2	.2	7.6	.2	
	Na-feld.	19.6		Albite 1	.6	18.6	.4	
Quartz	Quartz	.4		.....	.....	.....	.....	.4
Total	.....	.....		.....	58.4	38.4	2.8	.4

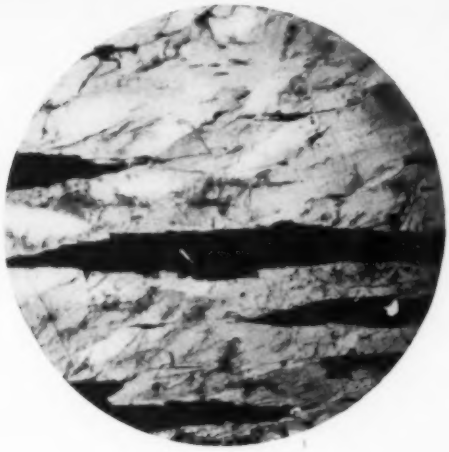
Classification:

Popular: Microcline microperthite

Technical: Microcline hypoperthite.

12. "Orthoclase," near Unionville, Chester County, Pennsylvania. (Specimen 996.)

Microscopic examination, thin section: Typical microcline microperthite with inclusions of diopside, quartz, and untwinned feldspar thought to be anorthoclase.



A

B

A. Microcline microperthite (hypoperthite), called "Amazonstone," Mineral Hill, Pennsylvania. Polarized light. ×30. Specimen 964.

B. Microcline microperthite (hypoperthite), called "Amazonstone," near Florissant, California. Polarized light. ×30. Specimen 971.

Extinction angles, crushed fragments:

Potash phase	(010)	7.0°
	(001)	17.0°
Soda phase	(010)	13.0°
	(001)	1.0°

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	79.0	2.0
Na-feldspar	19.0	89.0
Ca-feldspar	2.0	9.0

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar	Silica
Soda microcline	71.5	79.0	19.0	2.0	0.
Oligoclase	24.1	2.0	89.0	9.0	0.
Quartz	.....	.....	.....	.....	100
Soda microcline	.....	56.5	13.6	1.4	.....
Oligoclase	.....	.5	21.4	2.2	.....
Quartz	.....	.....	.....	.....	4.4
Total	.....	57.0	35.0	3.6	4.4

Classification:

Popular: Microcline microperthite

Technical: Microcline hypoperthite

13. *"Microcline Amazonstone," near Florissant, California.* (*Specimen 971.*)

Microscopic examination, thin section: Intergrowths of potash and soda rich feldspars. Microclinic twinning beautifully shown.

Extinction angles, crushed fragments:

Potash phase	(010)	5.5°
	(001)	17.0°
Soda phase	(010)	12.0°
	(001)	4.0°

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	80	3
Na-feldspar	18	85
Ca-feldspar	2	12

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar	
Soda microcline....	69.6	80	18	.2	.....
Oligoclase.....	30.4	3	85	12	.....
Soda microcline....	.....	55.6	12.6	1.4	.....
Oligoclase.....	.....	.9	25.9	3.6	.....
Total.....	.....	56.5	38.5	5.0	100

Classification:

Popular: Microcline microperthite.

Technical: Microcline hypoperthite.

14. "Oligoclase," Eganville, Ontario, Canada. Specimen 962.)

Microscopic examination, thin section: The specimen has been incorrectly identified; it is a microcline microperthite—not oligoclase. There is some oligoclase in the specimen but it is intergrown with soda microcline. Besides the feldspar phases, biotite and quartz are present.

Extinction angles, crushed fragments:

Potash phase.....	(010).....	6.0°
	(001).....	18.0°
Soda phase.....	(010).....	5.0°
	(001).....	1.0°
Zone ⊥.....	(010).....	5.0°

Index of refraction, soda phase, beta, 1.546

Inferred Composition	Potash Phase	Soda Phase
K-feldspar.....	70	8
Na-feldspar.....	28	75
Ca-feldspar.....	2	17

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	Na-feldspar	K-feldspar	Ca-feldspar	
Soda microcline....	62	70	28	2	.....
Oligoclase.....	38	8	75	17	.....
Soda microcline....	.....	44.4	17.3	1.2	.....
Oligoclase.....	.....	3.2	27.4	6.5	.....
Total.....	.....	47.6	44.7	7.7	100.0

Classification:

Popular: Microcline microperthite.

Technical: Microcline hypoperthite.

A

B

A. Microcline microperthite (hypoperthite), called "Oligoclase," Eganville, Ontario, Canada. Polarized light. ×30. Specimen 962.

B. Anorthoclase, Frederiksvärn, Norway. Polarized light. ×30. Specimen 981.

15. *"Anorthoclase," Frederiksvärn, Norway. (Specimen 981.)*

Microscopic examination, thin section: There is a faint suggestion of microclinic twinning on a very fine scale. Some areas appear to be entirely free and have slightly different optical characters. There are veinlets of oligoclase and stringers of soda microcline but they are too small for quantitative measurements.

Extinction angles, crushed fragments:

Untwinned	(010)	11.0°
	(001)	2.9°
Twinned	(010)	3.5°
	(001)	9.5°

It follows from examination of the chart, Figure 8, that the untwinned fragments are orthoclasic, that is monoclinic (?), while the twinned pieces are microclinic, triclinic (?).

Inferred composition:

K-feldspar	45
Na-feldspar	53
Ca-feldspar	2

CHEMICAL AND MICROSCOPIC ANALYSES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	H_2O	Total
1	65.19	19.99	.63	.48	7.03	7.08	.38	100.78
2	66.08	18.77	.....	.37	7.68	6.54	.....	99.44

	K-feldspar	Na-feldspar	Ca-feldspar
1	44.09	57.65	2.26
2	44.41	53.82	1.77
Microscopic	45.0	53.0	2.0

Classification: Anorthoclase, potentially eutectoperthite.[1]

16. *"Orthoclase," East DeKalb, St. Lawrence County, New York. (Specimen 995.)*

Microscopic examination, thin section: A typical microcline microperthite, not orthoclase. A few inclusions of apatite, calcite, phogopite, and hematite. The latter due to exsolution.

Extinction angles, crushed fragments:

Potash phase	(010)	8.0°
	(001)	11.0°
Soda phase	(010)	10.0°
	(001)	4.5°

[1] *Analyses 1 and 2.* Carl Hintze, *Handbuch der Mineralogie.* Kalifeldspath, CCXXIX and CCXXX, 1414, 1892.

Inferred Composition	Potash Phase	Soda Phase
K-feldspar	72	10
Na-feldspar	25	80
Ca-feldspar	3	10

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar
Soda microcline	51.5	72.0	25.0	3.0
Oligoclase	48.5	10.0	80.0	10.0
Soda microcline	.....	36.0	13.0	2.0
Oligoclase	.....	5.0	39.0	5.0
Total	.....	41.0	52.0	7.0

CHEMICAL AND MICROSCOPIC ANALYSES

Analysis. A. A. Robbins, Collection on exhibition in the New York State Museum, Albany, N.Y.

SiO_2	Al_2O_3	MgO	CaO	Na_2O	K_2O	H_2O	SO_3	Total
68.60	19.82	.14	.96	4.57	5.25	.30	tr	99.64

	K-feldspar	Na-feldspar	Ca-feldspar
Chemical	41.5	51.8	6.7
Microscopic	41.0	52.0	7.0

Classification:

Popular: Microcline microperthite.

Technical: Microcline eutectoperthite.

17. *"Orthoclase, var. Delawarite," Lenni, Delaware County, Pennsylvania. (Specimen 991.)*

Microscopic examination, thin sections: It is evident that this specimen is what a few mineralogists call antiperthite.[1] That is, the host is a soda-rich feldspar, while the blebs or "inclusions" are high in potash.

The nomenclature here adopted calls for hyperperthite. This type is rare in nature.

Extinction angles, crushed fragments:

Soda phase	(010)	14.0°
	(001)	4.7°
	(010)	5.5°
	(001)	16.5°

[1] Ernst Weinschenk and R. W. Clark, *Petrographic Methods* (1912), p. 326.

A

B

A. Microcline microperthite (eutectoperthite), called "Orthoclase," East DeKalb, St. Lawrence County, New York. Polarized light. ×30. Specimen 995*x*.

B. Antiperthite (hyperperthite), called "Orthoclase," var. Delawarite," Delaware County, Pennsylvania. Polarized light. ×30. Specimen 991.

QUANTITATIVE MICROSCOPIC ANALYSIS

Phase	Percentage	K-feldspar	Na-feldspar	Ca-feldspar	Silica
Potash albite	80	8	90	2	0
Primary soda microcline	10	87	10	3	0
Primary oligoclase	2	17	80	3	0
Myrmekite	2	17	75	3	5
Quartz	3	0	0	0	100
Secondary soda microcline	2	89	8	3	0
Potash albite		6.4	71.9	1.6	0
Primary soda microcline		8.7	1.0	.3	0
Primary oligoclase		.34	1.6	.06	0
Myrmekite		.34	1.5	.06	.1
Quartz					3.0
Secondary soda microcline		2.7	.20	.09	0
Total		2.7	76.30	2.11	3.1

Classification:

Popular: Antiperthite.

Technical: Hyperperthite.

APPLICATIONS OF THE MINERALOGRAPHY OF THE FELDSPARS TO GEOLOGICAL PROBLEMS

CASE ONE—LOCATION OF A FAULT

The Problem.—One of the graphite properties in the Adirondack Mountains visited by the writer in 1917[1] had been abandoned because the ore was cut off by a fault. The writer had this information when he entered the field, but to his unpleasant surprise he was unable to locate with any satisfaction the faults even though slickensided surfaces were found on the walls of the old workings.

As it was deemed very desirable to locate the faults with some degree of accuracy, the writer carried the problem into the laboratory for solution.

Method of Attack.—Preliminary examination of the graphite-bearing schist showed that it was chiefly composed of potassic feldspar. The suggestion of Rosenbusch[2] that the development of microcline structure in orthoclase is due to pressure was recalled.

[1] H. L. Alling, *New York State Museum Bull. 199*, pp. 61, 68–70, 1918.

[2] Rosenbusch-Iddings, *Microscopic Physiography of the Rock Making Minerals*, p. 320.

The writer has already discussed this phenomenon and has reached the conclusion that pressure does not *produce* microcline from orthoclase; it only starts and accelerates the change. This suggestion seemed a promising method of attack. Unless the graphite-bearing schist had suffered very severe regional metamorphism the potassic feldspar would still exist in the metastable condition which we know as orthoclase. But under the stress and jar of faulting the feldspar would take on the microclinic type of twinning as a consequence of the inversion of orthoclase to microcline. Microscopic examination would locate the fault.

Another trip into the field resulted in a collection of a suite of specimens from numerous localities in and about the old workings.

Petrographic Study.—Examination of the slides from these specimens showed that the writer's supposition was entirely correct. Some were composed of orthoclasic feldspar while others showed microclinic types.

Interpretation.—It was concluded from quantitative microscopic analyses that specimens which showed a high orthoclasic content came from areas that were free from faulting, and that specimens showing soda microcline were situated in zones affected by faulting.

Results.—In 1918, the following year, the writer took his map of the Rock Pond workings, giving the results to the petrographic study, back into the field and erected piles of stones where faulting had been deduced from the slides. From the position of these cairns it was possible to trace a group of faults that cut off the ore on three slides. Careful examination of the walls of the pits revealed conclusive evidence of the correctness of the interpretation. Slickensides and breccias were where the microscope had indicated that they should be.

CASE TWO—ORTHO-AMPHIBOLITES VERSUS PARAMPHIBOLITES

The Problem.—In many pre-Cambrian areas where ancient sediments have been invaded by igneous rocks, and subjected to contact and regional metamorphism, the character of the original rocks becomes profoundly altered, both in regard to mineralogical and structural relationships, under these forces. Both limestones and calcareous shales become metamorphosed into paraschists,

which are composed largely of hornblende. These are hornblende schists, or paramphibolites. In a similar manner old basic eruptives, such as diabases, diorites, and gabbros, are metamorphosed to orthoschists and gneisses. They may be called ortho-amphibolites. "The origin of the amphibolites is a question of the highest importance in the elucidation of the geology of the [Haliburton and Bancroft] area, as well as one of great interest from a petrographical standpoint . . . . [examination has] shown, beyond a doubt, that amphibolites, which, in many cases cannot be distinguished apart, have been produced by the action of granitic instrusions on limestone. There is also reason to believe that other amphibolites have been produced in still other ways [for there is evidence that some amphibolites are] of undoubted igneous origin."[1]

In the Adirondack Mountains ortho- and paramphibolites present a difficult problem. In areal mapping this problem is of scientific interest only, but when these are encountered upon mining properties the distinction between the two types becomes essential. The writer has encountered amphibolites[2] where it was impossible to classify the rock. In some doubtful cases the rocks were studied petrographically.

Petrographic Study and Interpretation.—Specimens were collected from rock masses where field relations pointed to a definite origin. Microscopic examinations revealed striking similarities and a few differences. The similarities need not be touched upon; it is the latter that are important. If the rock is sedimentary in origin and derived from calcareous shales as Cushing suggests,[3] quartz would be expected to occur, as unmetamorphosed shales almost universally carry some quartz. Thus if any original quartz is present in an amphibolite, it gives it a sedimentary look, for basic (subsalic, femic) rocks are usally lacking in this mineral. On the other hand the absence of quartz suggests an igneous origin,

[1] F. D. Adams and A. E. Barlow, Canada, Dept. Mines, *Geol. Surv. Mem. 6*, pp. 158–59, 1910.

[2] See J. F. Kemp and H. L. Alling, "The Geology of the Ausable Quadrangle," *New York State Mus. Bull.* (In preparation.)

[3] H. P. Cushing, *New York State Mus. Bull. 169*, p. 19, and *Bull. 191*, p. 15, 1914.

but this may not be a safe criterion, in that quartz may have been reorganized into meta- and trisilicates.

Seeking for a more reliable distinction the pyroxene-amphibole (the pyribole of Johannsen)[1] content was examined. It is held by many geochemists[2] that pyroxene is a high-temperature mineral, while amphibole is a lower-temperature form. The change from one to the other being a paramorphic (or "autometamorphic") one —a change readily brought about by the stresses of dynamic and static metamorphism—the inversion of pyroxene to amphibole furnishes some aid in the problems in hand. If a large amount of pyroxene, such as augite, is found in an amphibolite it suggests an igneous origin. But under the stress of severe metamorphism this inversion may be complete. Martin[3] found this to be true of the amphibolite inclusions in the granitic rocks in St. Lawrence County. Thus the absence of augite does not prove a sedimentary parentage, but merely suggests it. This criterion, like the former, is therefore regarded as inconclusive.

Hunting for additional criteria, the writer investigated the feldspars in turn. It was found that the igneous types usually contained a simple range of feldspars, such as 10 per cent of soda orthoclase and 20 per cent of andesine, while the sedimentary rocks frequently exhibited a motley collection; covering a much wider range. Very commonly soda orthoclase, soda microcline, microperthite, oligoclase, and labradorite were seen in a single microscopic slide.[4]

Adams[5] states that the amphibolite occurring near Jack Lake, Ontario, to which an igneous origin must be ascribed, is "composed almost exclusively of hornblende, and plagioclase feldspar. The hornblende is rather light green in color in ordinary light. . . . . The plagioclase is clear and fresh in appearance, and rather basic

[1] Albert Johannsen, *Jour. Geol.*, XIX, p. 319, 1911.

[2] J. V. Elsden, *Principles of Chemical Geology*, p. 114, 1910; Becke, *Tsch. Mineral und Petrog. Mitt.*, *16*, pp. 327–36; F. W. Clarke, *U.S. Geol. Surv. Bull. 616*, p. 386; Lacroix, *Mineralogie de la France*, I (1893–95), pp. 668–69.

[3] J. C. Martin, *New York State Mus. Bull. 185* (1916), p. 157.

[4] H. L. Alling, *Amer. Jour. Sci.* (4), XLVIII (1919), pp. 61–62.

[5] F. D. Adams, "On the Origin of the Amphibolites of the Laurentian Area of Canada," *Jour. Geol.*, XVII (1909), pp. 1–18; F. D. Adams and A. E. Barlow, "Geology of the Halburton and Bancroft Areas," Province of Ontario, Canada, Dept. of Mines, *Geol. Survey Branch, Mem. 6* (1910), pp. 160–61.

in character . . . . [and limited to] a single species . . . . , a large proportion of [which] is frequently untwinned." The paramphibolites derived from the action of granitic intrusives and metamorphism upon Grenville limestone "are composed of quartz, microcline, orthoclase, and plagioclase."[1] This selective habit of the feldspars is explained on the ground that in the freezing of a magma the feldspars "split along the eutectic line." If the feldspar composition, in the magma, was on the potash side of the eutectic line the resulting crystals would be dominantly the orthoclase type of feldspar, while if it was on the other side plagioclase (plus a little potash feldspar) would result. But if the position of the molten feldspar was on or near the eutectic line the solid minerals would be divided on freezing into orthoclase (carrying a little soda feldspar in solid solution) and plagioclase.

Conclusion.—The criteria may be summed up as follows:

Sedimentary Origin	Igneous Origin
Original quartz	High pyroxene content
Motley collection of feldspars	Evenly "split" feldspars

How successfully these criteria have been applied to amphibolites whose origin was not forthcoming from the field relations cannot as yet be stated, but hope is entertained that some progress has been made in this difficult problem.[2]

APPENDIX[3]

THE SOLUBILITIES OF THE FELDSPAR COMPONENTS[4]

In order to understand the nature and construction of minerals from a mineralographic point of view, it is preferable to commence our consideration with reference to the state of homogeneous fusion. Although it may be that certain pairs of silicic salts cannot

[1] F. D. Adams, "On the Origin of the Amphibolites of the Laurentian Area of Canada," *Jour. Geol.*, XVII (1909), p. 10.

[2] Since this was in type a recent paper in this Journal on the "Feldspar Method" of distinguishing sedimentary and igneous metamorphics has appeared.

[3] This section is introduced to furnish the reader who is not familiar with the meaning and interpretation of thermo-equilibrium diagrams a simple explanation of their construction and value.

[4] The manner of presenting this topic has been patterned very closely after that of Rosenhain (*Introduction to Physical Metallurgy*, p. 78, 1915). It is of interest to note the similarity of mineralography to metallography.

be made to mix in all proportions while in the molten condition, it is highly probable that, in the great majority of cases, they can be mixed with one another in the fluid state in any relative proportion. In this respect these fluids resemble such liquids as water and alcohol. We may, in fact, safely carry this analogy much further, and regard mixtures of two molten silicic salts as simple solutions of the two constituents in one another. Since our interest naturally centers in the solid mineral which results from the solidification of such melts the question which lies before us is what happens to a mutual solution of two silicic salts when the temperature is lowered so that the material undergoes solidification?

The answer is that there are two opposite modes of solidification adopted by such systems, and a range of intermediate modes connecting these extremes. The one extreme is (*a*) the case in which on solidification the mineral crystallizes while still remaining a solution, i.e., the crystals which are formed ultimately attain the same composition as the molten liquid from which they crystallize. Such crystallized solutions are usually termed "solid solutions" in view of the fact that they are at the same time solids and solutions. This is the case when perfect isomorphism exists.

Such solid solutions should not be regarded as compounds, and no single chemical formula can be employed to express the mineral as a whole.

The other extreme of the mode of solidification (*b*) is that in which the state of solution which exists in the liquid condition is largely or entirely destroyed by the passage into the solid state, the two constituents separating more or less completely during the process of crystallization. This condition occurs when limited isomorphism prevails.

THE EQUILIBRIUM DIAGRAM

The most comprehensive and satisfactory method of presenting and describing the nature and constitution of minerals belonging to a given system consists in a diagram—the thermo-equilibrium diagram—which is based primarily upon thermal data. The construction of such a diagram is based upon the determination of the temperature of the specimen at various times during a heating or cooling process. The usual method consists in taking temperature

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FIG. 14.—Diagram illustrating the construction of a thermo-equilibrium diagram of two components which are completely soluble in each other in the solid condition. The "partitions," 1, 2, 3, 4, and 5, are time-temperature curves, while the cigar-shaped area is the conventional form of the equilibrium diagram.

readings at fixed intervals of time and then plotting the results with temperatures as ordinates and times as abscissas. A time-temperature curve is thus obtained which indicates the behavior of the mineral in a most direct way. So long as the substance is simply raised or lowered in temperature at a steady rate, this curve follows a smooth course; a departure from this smoothness indicates that there has been either an evolution or an absorption of heat within the specimen. Such a change in the shape of the curve indicates a change of state, either in phase, or in modification. Time-temperature curves are obtained for a binary system from specimens composed of the two constituents in varying amounts from 100 per cent of one to 100 per cent of the other. The construction of the equilibrium diagram from these time-temperature curves is illustrated in Figure 14. Five time-temperature curves are shown as partitions in the end of a box, numbered 1, 2, 3, 4, and 5. The critical points or places where the curves change in direction are indicated by A', B, D, F, and H'. These mark the points where crystallization commences and A, C, G, and H, indicate where the solidification is complete, if the specimen is allowed to cool. If, however, the specimen is reheated, it will theoretically at least pass through the identical behavior except in the reverse order. That is, the points A, C, G, and H are determined by the initial melting, and the points $A'B$, D, F, and H' by complete liquefaction.

Now these time-temperature curves (partitions) enable us to construct the equilibrium diagram by projecting or drawing construction lines parallel with the base from the points already mentioned back to the vertical plane, as is indicated in Figure 14. Removing the time-temperature curves, which are merely scaffolding, the diagram remains as a conventional method of indicating the crystallization behavior of an isomorphous series, i.e., a series of solid solutions.

In Figure 15 the opposite extreme of a binary system is shown. The diagram is constructed in the same manner, from the projection of the critical points of a series of time-temperature curves. In this case the two components are completely insoluble in the solid state. It will be noticed that the upper line, $A_1B_1E_1$, repre-

senting the freezing temperatures (and called the liquidus) falls off or is depressed as amounts of the second component are added,

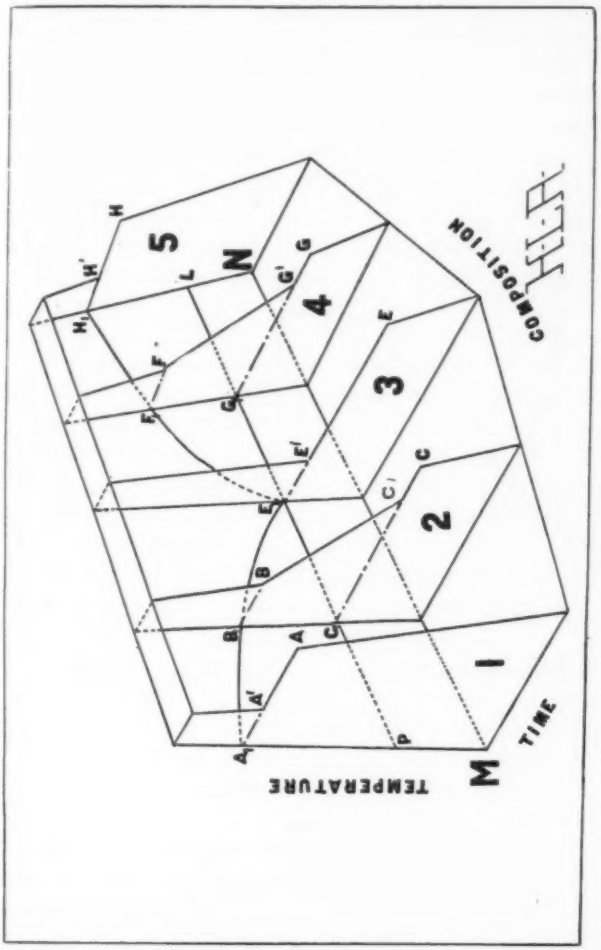

FIG. 15.—Diagram illustrating the construction of the thermo-equilibrium diagram of a eutectiferous system

until (near the center of the present diagram) a point is reached where the sum of the two components freezes at a temperature lower than in any other proportion. This is the "eutectic point"

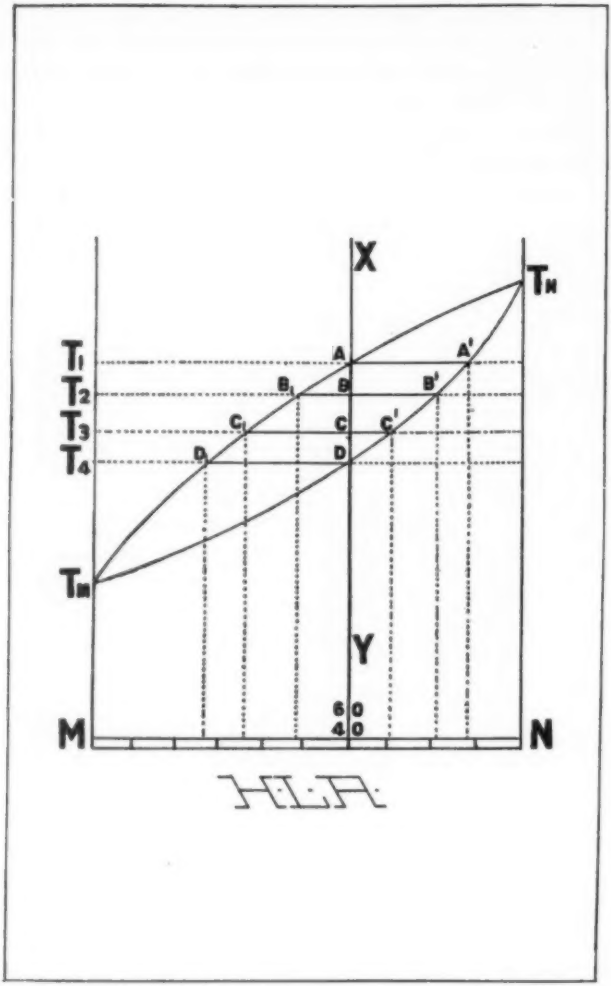

FIG. 16.—Thermo-equilibrium diagram of a series of solid solutions. Composition of melt taken as 60 per cent of *N* and 40 per cent of *M*. For discussion see text. Roozeboom's Type I.

(εὖ, easy, τηκτός, melting). The line $PC_1E_1F_1L$ is the other curve of the diagram, the solidus.

Now having described the manner in which an equilibrium diagram is constructed let us see what it can tell us of the process of solidification of an isomorphous series. Figure 16 is a diagram of such a system (Type I of Roozeboom's classification), the time-temperature construction curves not being shown. The temperatures form the ordinate and the composition the abscissa. Above the liquidus line $T_MD_1C_1B_1AT_N$ the solution of the two components as a liquid is a mutual one, that is they mix in all proportions. Between the liquidus and the solidus—the lens-shaped area—is the area in which solidification is going on and is occupied by both liquid and solid phases. Below the solidus the system is solid. Now let us trace in detail what happens during the freezing of a melt composed of 60 per cent of N and 40 per cent of M as is indicated by the vertical line XY. Above A the system is liquid, but as the temperature, falling, reaches the liquidus line, crystallization commences, precipitating crystals of the composition A'. The composition of such a crystal is obtained by constructing the horizontal dash line from A to the solidus. Thus the first crystal formed has a composition of A'. The remaining liquid has a composition of A. With continued lowering of the temperature the point represented by B is reached. The composition of the crystal is B' and that of the liquid is B_1.

Temperature	Composition of Crystal	Composition of Liquid
T_1	A'	A
T_2	B'	B_1
T_3	C'	C_1
T_4	D	All liquid frozen

It will readily be seen that in the phenomenon above, where we are assuming, for the time being, that no adjustment of the crystals between themselves or between the crystals and the liquid takes place, the resulting crystals will have a wide range in composition, or a single crystal will be built up concentrically of zones of variable composition. It follows from the examination of the diagram that the center of such crystals will have a

composition richer in the component that possesses the higher freezing-point than the margins. Such zonal crystals are common among the plagioclase feldspars. Not all zonal textures, however, are to be explained in this way, as will be explained later in more detail. All available information leads to the conclusion that this type of diagram is the one to which the plagioclase feldspars (the soda-lime series) are to be assigned. In the field of mineralography our knowledge of other and similar systems is very incomplete. In addition to the plagioclase feldspars, the garnets, the scapolites, the micas, the alums, and certain ranges of the pyroxene and amphibole families may be mentioned. But in the field of metallography, binary systems of solid solutions are better understood. The following systems may be noted: Ag-Au, Ag-Pd, Au-Pd, Bi-Sb, Co-Fe, Co-Ni, Cu-Pd, Cu-Pt, Fe-Mn, In-Pb.[1] There is no fundamental difference between isomorphous minerals and the alloys belonging to this group.

Now let us examine in more detail the other extreme (*b*), that of a eutectiferous system, the two components of which are entirely insoluble in each other when in the solid state. In Figure 17 the composition of the melt chosen is the same as that used before, namely 60 per cent of *N* and 40 per cent of *M*. On cooling the melt the freezing commences at *A;* the resulting crystal having a composition of A_1 or pure *N*, the liquid, a composition of *A*. This can be expressed by saying that the composition of the crystal "varies" or "slides" down the line $A_1B_1C_1D_1$ while that of the remaining liquid "slides" down the liquidus from *A* through *B* and *C* toward *E* where it freezes, but on passing to the solid phase the solution *E* is rendered a mechanical mixture as the two components separate, theoretically at least, into pure *N* and pure *M*. This mechanical mixture is termed the eutectic mixture. This tells us how such a system will look under the microscope, either in thin sections or as etched polished slabs. It will consist of crystals of pure *N* surrounded by minute crystals of pure *M* and pure *N*. The groundmass of the small crystals will be the eutectic mixture. It is possible to reverse the scheme and determine the composition of the original melt by determining the

[1] C. H. Desch, *Metallography* (1913), p. 401.

amount of the crystals of pure *N* and of the small crystals which constitute the eutectic mixture, and "sliding" back up the lines until *A* is reached.

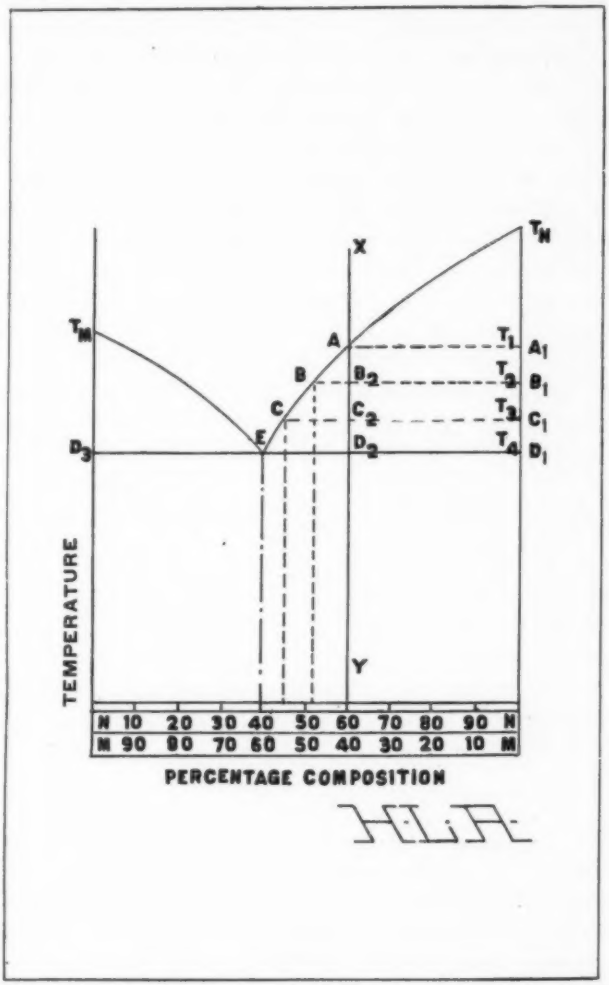

FIG. 17.—Thermo-equilibrium diagram of a eutectiferous system

We are not greatly interested in Figure 17 for it was introduced as a stepping-stone to Figure 18 with which we shall have much to do. Intermediate between the two diagrams already discussed is a type of diagram shown in Figure 18 (Roozeboom's Type V) which represents a condition where limited solubility between the two components prevails in the solid condition. The lines FD_3 and GD_1 are the assumed solubility lines, showing the limits of solubility. Again, going through the same procedure as before, we take a melt composed of 60 per cent of N and 40 per cent of M and allow the temperature to fall to T_1 indicated by the point A on the liquidus. At this point the composition of the crystals separating into solid form is A. This is not pure N as it would be in the previous Figure 17 but it is a solid solution, 91 per cent N and 9 per cent M, the percentage being found by dropping a perpendicular line from A_1 to the "Percentage Composition" scale at the bottom of the Figure 18. The liquid remaining has an approximate composition of A. As the temperature falls the change in the composition of the crystals is represented by the liquidus curve from A through B and C toward E. When the eutectic point E is reached the eutectic mixture freezes, being composed of solid solution D_1, 80 per cent N and 20 per cent M, and solid solution D_3, 20 per cent N and 80 per cent M. Thus the resulting solid mineral is composed of crystals—solid solutions—having a range in composition represented by the curve A_1D_1 surrounded by the eutectic mixture which is composed of two solid solutions, D_3 and D_3.

The discussion of these diagrams has been merely for the purpose of attempting to explain the meaning and the use of what are known as thermo-equilibrium diagrams.

CONCLUSIONS

1. The application of the phase rule and thermo-equilibrium diagrams to the feldspar system enables the mineralogist and the petrographer to secure a much better conception of the true physical-chemical nature of these minerals. This method of investigation throws considerable light upon the character of many other mineralogical systems.

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2. The thermo-equilibrium diagram of the iron-carbon binary system offers the mineralogist a method of studying the alloys which

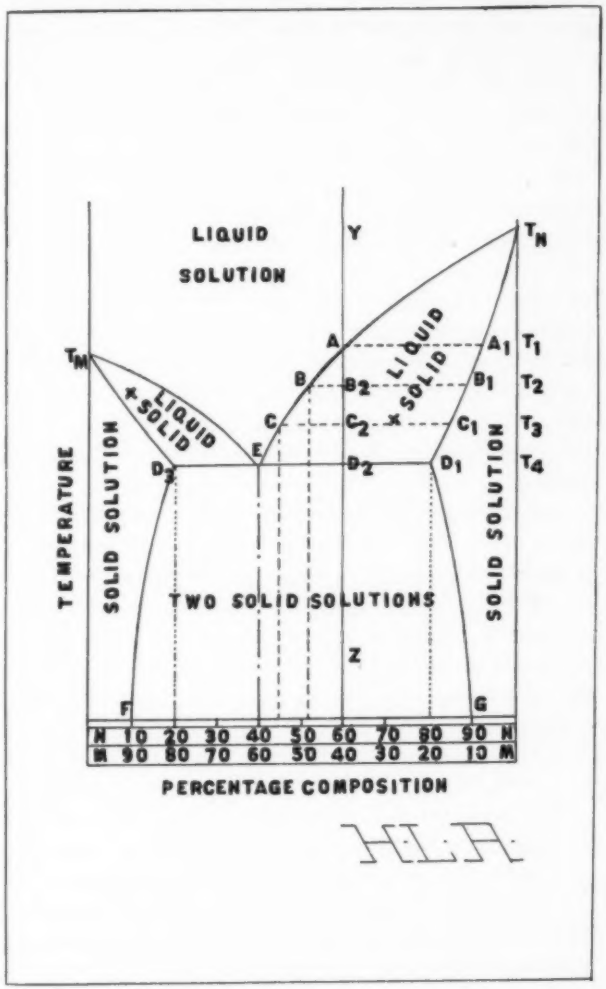

FIG. 18.—Thermo-equilibrium diagram of a eutectiferous, limited-solubility system. The general type probably represented by the potash-soda series.

in his domain are called minerals. Familiarity with this system is of great assistance in clarifying the problems of mineralogy.

3. The feldspars belong to a five-component system, of which the end members are the potash, soda, lime, barium, and carnegieite feldspars. For most purposes it is only necessary to consider the potash, soda, and lime components. Every specimen of feldspar found in nature contains a certain amount of each of these three components.

4. The plagioclase and the hyalophane series constitute a series of solid solutions. The potash-soda and the potash-lime series possess only limited solubility, and constitute eutectiferous systems.

5. It is believed that both the potash and the soda feldspars are dimorphous, each existing in two isomeric forms: each component crystallizing either in monoclinic or triclinic modifications, depending upon the temperature and the viscosity of the magma; that orthoclase and albite are high-temperature modifications and that microcline and possibly (?) barbierite are relatively low-temperature forms.

6. The complete solubility of albite in anorthite, and vice versa, presupposes that their chemical structures are analogous, even though albite is usually regarded as a "trisilicate" and anorthite an "orthosilicate." This presupposes that the feldspars are aluminosilicates. Since orthoclase and albite (components) are not completely soluble in each other (when perfect equilibrium prevails), they probably possess somewhat dissimilar chemical structures.

7. Some feldspars contain nephelite in solid solution but this mineral cannot be regarded as isomorphous with the normal feldspars. Therefore the mineralographic term "solid solution" is more comprehensive than the crystallographic term "isomorphism."

8. All feldspars are solid solutions and mixtures of solid solutions, and therefore do not possess definite chemical compositions. No single chemical formula can be assigned to a single species. Inasmuch as labradorite is a mineral, the chemical composition of which is *not* fixed, and, furthermore, the mineral is often found zonally grown, the usual definition of a mineral as a *homogeneous*

natural inorganic substance of *definite chemical composition* needs revision.

9. That the plagioclase feldspars are not "molecules," portions of which are "replaceable" by analogous units. This statement applies with almost equal force to the potash-soda series as well.

10. While the term "mixed crystals" is frequently used to signify "solid solutions," yet it should be avoided for the sake of clearness.

11. Perthite is an intergrowth of two (or more) solid solutions, and not an intergrowth of the simple components, microcline (or sometimes orthoclase) and acid plagioclase. The two phases are solid solutions, one rich in potash and the other rich in soda.

12. That most perthites are not the *direct* result of the freezing of a magma, but are the result of *subsequent* processes, where the decrease in solubility of one phase for the other with falling temperature is the principal factor. The inversion of orthoclase to microcline is regarded by some as also a contributing cause. Perthites are commonly the result of the process here called "exsolution." Such perthites (or "perthoids") are analogous to pearlite in steels.

13. That many anorthoclase specimens are supersaturated, undercooled metastable solid solutions, potentially perthite through the intermediate stages of crypto- and microperthite.

14. That intergrowths of potash-rich and lime-rich solid solutions occasionally are found. To such intergrowths the term *oranite* (the first two letters of *or*thoclase and *an*orthite and the ending *-ite*) has been applied.

15. That the feldspars of many basic monzonites and the granodiorites are approaching, as the limit, the potash-lime binary system. But because such feldspars are not as viscous at their melting temperatures as the potash-soda series, they separate more completely into definite identities, and consequently the *oranitic* feldspars are not usually recognized as such.

16. The significance of the process of exsolution is that many so-called inclusions in mineral grains are due to secondary processes, and consequently are of late rather than of early development.

This complicates the methods of determining the order of crystallization of the minerals in a rock.

17. Primary perthite, due to the freezing of the eutectic mixture, analogous to ledeburite in steels, is probably uncommon in nature.

18. The potash feldspar of pegmatitic origin, the usual museum variety of "orthoclase," is soda microcline and very rarely, if at all, "orthoclase." In fact orthoclase (nearly pure potash feldspar without microclinic characteristics) is very rare in nature.

19. Some "adularias" and "microclines" show microclinic twinning when examined in thin sections, but in thin plates or in crushed fragments they do not exhibit twin striations. The suggestion is strong that the pressure, which the specimens experienced in the grinding process in the preparation of the thin section, has hastened the inversion of the metastable soda orthoclase to soda microcline. This raises the question whether complete reliance can be placed upon thin sections in the identification of the feldspar species.

20. That microclinic and orthoclasic feldspars, with a content of the potash component higher than 85 per cent of the whole, are exceedingly rare in nature. It is far more accurate to speak of *soda* microcline and *soda* orthoclase than of microcline and orthoclase. Very frequently specimens of so-called microcline or orthoclase are found upon examination to be perthitic as well. Before assigning a name to a museum specimen, it should be microscopically examined.

21. That the inversion of soda orthoclase to soda microcline is often hastened by the pressure set up by regional or static metamorphism, but that the pressure does not *produce* soda microcline from soda orthoclase; it only initiates and accelerates the change. The tendency to change is inherent; the pressure merely starts the process.

22. All plagioclase specimens contain some potash component; the average is in the neighborhood of 5 per cent. It is more accurate to assume that the potash component is present to this extent than it is to ignore it altogether. The extinction angles of the soda-lime feldspars enable the petrographer to ascertain the amount of the soda component present but they do not determine the amount of the lime component. The percentage of the potash

feldspar is inferred from the average of the chemical analyses and the lime component is the remainder of the 100 per cent.

23. Many zoned plagioclase feldspars are to be explained by the process of normal crystallization under rapid chill instead of "magmatic corrosion." Homogeneous crystals of plagioclase are probably due to readjustment between crystal phases, or between them and the surrounding unfrozen liquid, in a slowly cooling magma. The degree of homogeneity is therefore a function of the rate of chill. Some zoned feldspars are undoubtedly the result of more complex processes in which the phenomenon of undercooling plays an important rôle.

24. The physical properties of a series of solid solutions are direct functions of the composition. If the properties, such as specific gravity, indices of refraction, extinction angles, etc., are plotted in conjunction with the thermo-equilibrium diagram they assume the form of smooth curves which rise and fall with the freezing (liquidus) curve. A break, a cusp, or a sharp change in direction in these curves at least suggests a discontinuity in the chemical properties of the system. Many involved formulas of minerals will probably be abandoned when they are shown to be solid solutions and mixtures of solid solutions of simple end members. The formula for hyalophane, "$(K_2,Ba)Al_2(SiO_3)_4$," cannot be entertained as possessing any true value.

25. In attempting to classify the feldspars on a basis of their true composition several new names have been proposed. See Figure 13 for schemes of classification. "Anorthoclase" is defined in paragraph 13 and its range delimited as $Or_{70}Ab_{30}$-$Or_{35}Ab_{65}$. The term "soda microcline" is confined to microclinic feldspars containing 10 to 30 per cent of the soda component. For albitic feldspars containing from 5 to 20 per cent of the potash component the term "potash albite" is proposed.

26. Because there are more contours of equal extinctions (isogonic lines) cutting the plagioclase side of the triangle (see Fig. 12, facing p. 251) than the number of those cutting the potash-soda side, the identification of the soda-lime feldspars can be accomplished with comparative ease. Nevertheless proper identification of the subspecies of the potash-soda series can be

made by means of the extinction angles on the different faces, together with the indices of refraction.

27. The application of these physical-chemical principles to the feldspar system furnishes, as a result, the means of solving practical geological problems. Two illustrations of the application of these conclusions to actual field problems are given on pages 275 to 279 inclusive.

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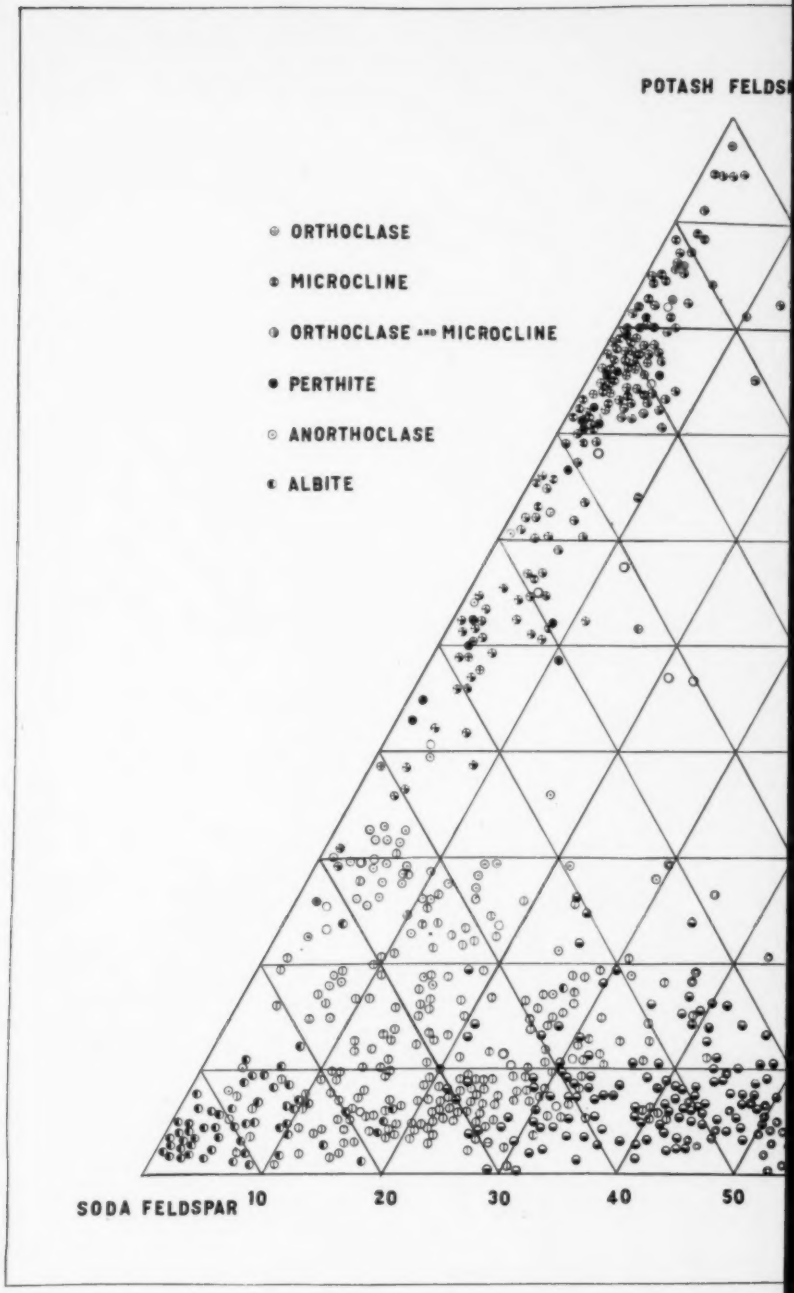
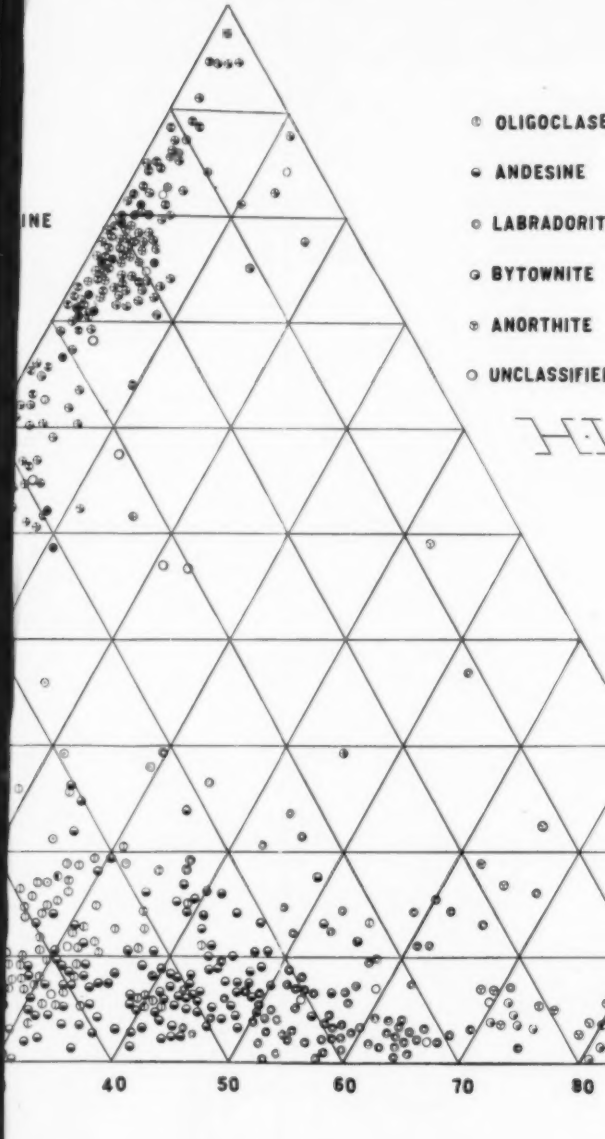


FIG. 19.—Plot of 954 recast chemical analyses of natural feldspars. The names assig
chemical analyses and are not those which the writer would employ in many cases. Note the
plagioclase feldspars contain considerable amounts of the potash component. The almost total



tural feldspars. The names assigned to the species here represented ar
mploy in many cases. Note the concentration of "microcline" and "orth
sh component. The almost total absence of representatives of the potas

ted are those published in connection with the "orthoclase" specimens and the fact that most potash-lime feldspars is also shown.

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